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EXPERIMENTAL INVESTIGATION OF THE PERFORMANCE OF TRAVELING-WAVE TUBES

FRANCIS TOFALO

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EXPERIMENTAL INVESTIGATION OF THE
PERFORMANCE OF TRAVELING-WAVE TUBES

by

FRANCIS TOFALO
B.S., U.S. Naval Academy
(1941)

SUBMITTED IN PARTIAL FULFILLMENT OF THE

REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

(1949)

Thesis
T6

ACKNOWLEDGMENT

Thanks are due to Professor J. B. Weisner for awakening the author's interest in the subject, and for his encouragement during the course of the research; to Mr. L. D. Smullin for his helpful suggestions in connection with the actual research and the preparation of the manuscript; to Mr. L. A. Harris who contributed greatly to the author's understanding of the subject; to Mr. P. M. Lally who supplied the electron guns; and to the technical personnel of the Research Laboratory of Electronics, who aided in the construction of the tubes, for their skilled assistance and willing cooperation.

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ABSTRACT

Application of the results of an investigation of propagation on a charge-free helix, conducted at the Research Laboratory of Electronics at M.I.T., has made possible the construction of traveling-wave amplifiers that have a higher stable gain than any of the earlier tubes constructed at that laboratory. The principal design changes include a reduction in the mean diameter of the helix and the use of a close-fitting glass tube for supporting the helix. Numerous mechanical difficulties, primarily in connection with the aligament of tube parts, presented themselves. These were overcome well enough so that two tubes, having nearly the same performance, were finally built.

Oscillograms of the gain versus beam voltage characteristic were obtained. These differ from similar oscillograms obtained earlier in that they do not show the customary interference pattern on either side of the principal gain peak. They also show that an increase in the input power causes an increase in the voltage of optimum gain. The curve of optimum voltage versus frequency is flat in the operating region, which is between 8400 and 9600 megacycles per second.

Curves of output power versus input power show that the gain is nearly constant only for very low values of input power, and that saturation limits the maximum power

output to about 50 mw. Maximum stable gains of about 23 db over a bandwidth of more than 1200 megacycles per second were obtained.

Measurements were made which indicate that there is a change in phase shift of the output which is a linear function of the beam voltage. Increasing the beam voltage by 50 volts results in a 4 radian decrease in the phase angle by which the output lags the input. Converting this change of phase shift to a change in the phase constant of the growing wave provides a qualitative check on the theory.

A noise figure of 28 db above KTB was measured. This noise figure is independent of the beam current which indicates that the noise is probably due principally to partition noise, since the percentage of beam current arriving at the collector is also nearly independent of the total beam current. The results of an attempt to improve the noise figure by means of positive feedback were inconclusive and a more complete investigation should be made.

CHAPTER I

INTRODUCTION

General Information.

The traveling-wave amplifier which offers possibilities of high gain over wide bandwidths at microwave frequencies is the subject of a developmental program currently active at the Research Laboratory of Electronics at M.I.T. This paper deals with the construction and performance of tubes which were built as a part of this program. Chapter I serves as an introduction and describes the relationship of the particular tubes studied to the entire program. Chapter II deals with the techniques used in constructing the tubes including the numerous difficulties which were encountered, while measurements of tube performance, including interpretation of these measurements, are covered in Chapter III.

Simple Theory.

The operation of a traveling-wave amplifier may be considered as an extension of the principle of operation of the cascade klystron. Consider a cascade klystron in which the number of resonant cavities is large, and the drift space between cavities has been reduced to zero, so that the interaction space between the beam and the r-f fields existing in the cavities is continuous. Then if the proper coupling is provided between the cavities so that there is a constant phase delay between the fields existing in any

one cavity and the fields existing in the preceding cavity, it seems reasonable that the electron beam passing through the interaction space will be subjected to a continuous bunching action, and furthermore that there will be a continuous interchange of energy between the beam and the fields. If the fields are giving up energy to the beam, the device is a linear accelerator, whereas if the beam is giving up energy to the fields, it is a traveling-wave amplifier.

Although the above analogy may be useful in bridging the gap between klystrons and traveling-wave tubes, a more direct statement of the essential elements of the principle of operation is desirable. This principle was first suggested by Kompfner[1*] who pointed out that it is possible to achieve amplification by directing an electron beam along a wave-guiding system, provided that the following conditions are met. 1. The system must be capable of propagating a slow mode so that the phase velocity of propagation is nearly equal to the velocity of the beam. 2. The slow wave propagated by the system must have a component of electric field which is colinear with the direction of motion of the beam, since only by doing work against an opposing field can the beam electrons give up energy to the wave. Several analyses have since been made both for specific guiding systems and for the general case of an unspecified guiding system. Most of the analyses[2-5] have been made under the assumption of small signals, i.e., the change in the energy of any electron is but a small part of the initial kinetic energy of the electron. It is further assumed that in the absence of an

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[*] Superscripts refer to Bibliography.

electron beam the system is capable of propagating a single forward wave with a propagation constant whose real part is either negative or zero depending on whether the system is assumed to be lossy or lossless. Under these conditions the presence of an electron beam of the proper velocity near the system causes the single forward wave to break up into three forward waves and one reverse wave. The exact nature of the propagation constants of these four waves depends on whether the system is assumed to be lossy or lossless. In general, the reverse wave and two of the forward waves are characterized by propagation constants having negative real parts, so that these waves are attenuated with distance along the system. On the other hand, the propagation constant of the third forward wave has a positive real part, so that this wave grows in amplitude as it propagates along the system. Given these conditions it is only necessary to provide suitable means for introducing a signal onto the guiding system, and for removing the amplified wave from the system, in order to construct a traveling-wave amplifier.

Experimental Data Previously Reported.

A number of traveling-wave amplifiers have been built and their performance reported by various investigators. These tubes may be classified according to the power level and the nominal frequency at which they operate. In general all of them are characterized by wide bandwidths and rather high noise figures. The tubes with which this paper is

concerned are designed to operate at an output power level of several milliwatts and at a frequency of about 9000 megacycles per second. A summary of the performance of comparable tubes, as reported by other investigators, is tabulated below. This table may be used to integrate the results reported herein with the general developmental picture of tubes operating at the above-mentioned power level and frequency.

Reported by	Maximum gain	Band-width	Noise Figure	Oscillation	Osc. Wave-length
Field[6]	13 db	1000 mc/s	Not reported	Yes	Not reported
Tomner[7]	4.4 db	Not reported	Not reported	Yes	Not definite but longer than 4.2 cm.
Schreiter[8]	14 db	600 mc/s	31 db	Yes	Ranging from 3 to 9 cm.

The tubes reported on by Schreiter were developed under the same program as the tubes reported on in this paper. Details of the changes in design which were made to increase the stable gain are given on page 13 below.

Principal Design Features.

The design of the tubes whose performance is reported in this paper is patterned after a design first published by Pierce and Field[9], which has become a more or less conventional design for traveling-wave amplifiers. As shown

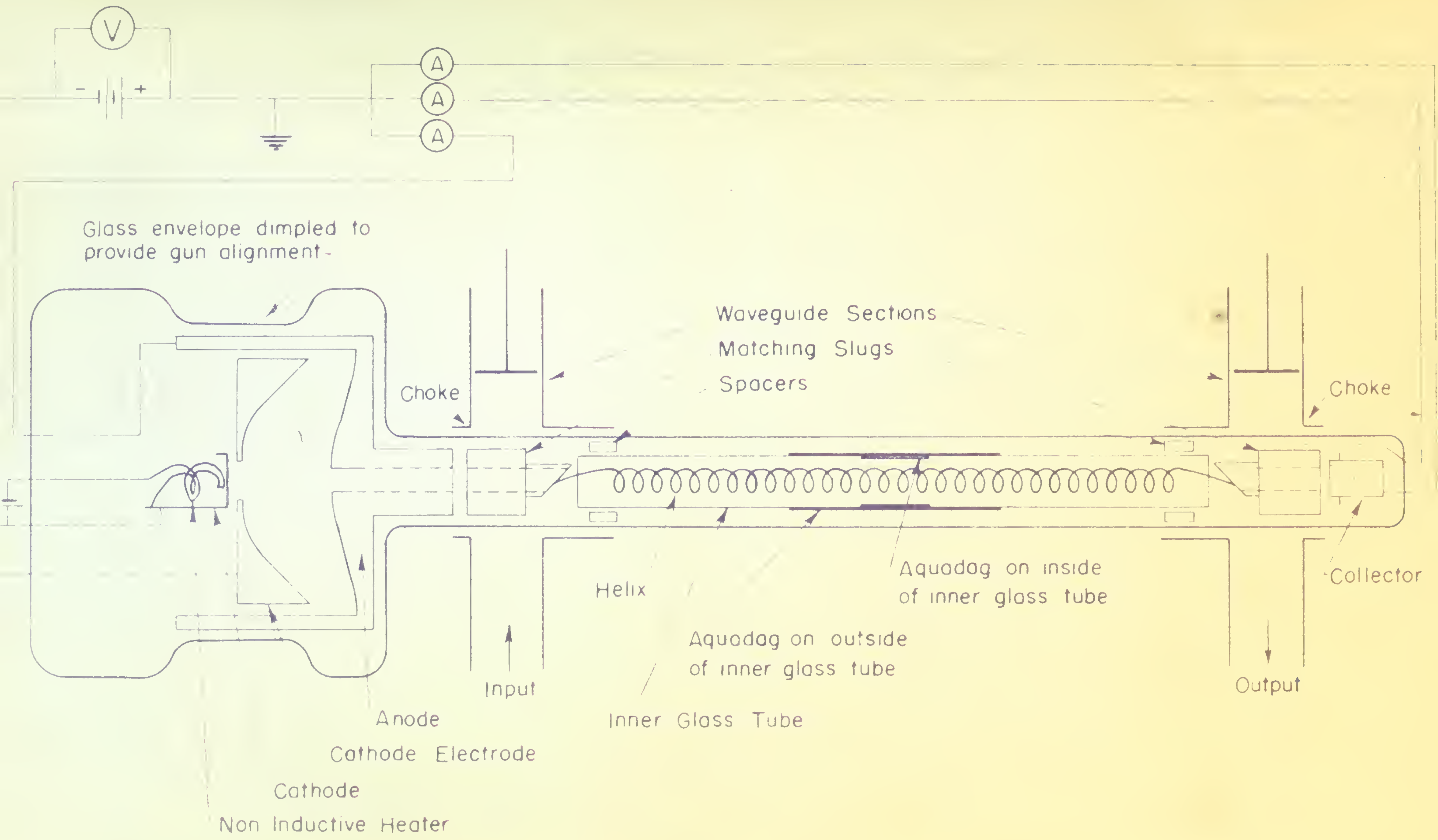


Figure I

SCHEMATIC of TRAVELLING-WAVE AMPLIFIER INCLUDING EXTERNAL CONNECTIONS

in Figure 1 the guiding system consists of a single wire helix. Over the main portion of the helix its pitch is held as nearly constant as possible. Near the ends, the helix pitch is gradually increased to form a smooth transition between the helix proper and its extreme ends. The extreme ends, which are pulled out fairly straight, are welded to matching slugs. An electron gun is provided at the input end of the tube to supply an electron beam which is shot through the inside of the helix along its longitudinal axis. Ideally the entire beam should traverse the whole length of the helix and be collected on the collector provided at the output end of the tube. Actually this situation was not achieved, a matter about which more will be said later. As shown in Figure 1, the tube is inserted into a set of input and output waveguide sections. The tapered-pitch portion of the helix enhances excitation of the desired slow mode, while the slugs make it possible to achieve a fair match between the waveguide and the helix. A choke is provided on the side of the waveguide away from the helix to reduce the undesired radiation into free space. A short section of the helix is surrounded by a lossy material in order to reduce the tendency of the tube to oscillate as a result of internal feedback caused by multiple reflections between the output and the input.

There are two major differences in design between these tubes and the preceding tubes of this program whose perform-

ance is summarized on page 10 above. One of these differences concerns the mean diameter of the helix which was reduced from about 0.125 inches to about 0.065 inches. The other difference concerns the configuration of the dielectric material necessary to support the helix, since the helix does not have enough mechanical strength to support itself. In the earlier tubes this dielectric material was in the form of four ceramic rods equally spaced around the outside of the helix. In these tubes, support for the helix is provided by a close-fitting glass tube which surrounds the helix. The reasons for making these changes involve considerations of gain, stability, and facility of construction.

The earlier tubes not only exhibited rather low gain but were also unstable. This instability manifested itself in the form of uncontrollable oscillations which appeared in spite of the presence of lossy material which had been placed along the helix for the express purpose of preventing such oscillations. It appeared that the oscillation wavelengths were somewhat greater than the signal wavelength. Now in order to have oscillations at any particular wavelength there must be gain at that wavelength. According to the theory, gain can be realized only when the beam velocity is very nearly equal to the phase velocity of the wave with the beam absent. This reasoning led to an investigation of the effect of dielectric supports on the phase velocity of a wave propagating along a helix[10]. The results of this investiga-

tion are summarized here to explain the reasons for making the design changes mentioned above.

Figure 2 shows curves of phase velocity as a function of frequency for various dielectric supports. The operating point of the earlier tubes corresponded roughly to point 1 of curve A. Clearly when the beam velocity was adjusted to produce gain at the frequency corresponding to point 1, the tube should also exhibit gain at the somewhat lower frequency corresponding to point 2. The question then arises whether gain and oscillations are equally probable at both points 1 and 2. Figure 3, which shows curves of the theoretical gain per unit length as a function of frequency, indicates that the gain at point 2 of curve A, Figure 2, should be somewhat greater than the gain at point 1 of the same curve. In the case of oscillations it should be recalled that oscillations require some sort of feedback. It is therefore necessary to examine whether this feedback is also equally probable at points 1 and 2. Waveguide junctions adjusted for a fair match at the frequency of point 1 will surely exhibit a bad mismatch at the frequency of point 2, with the result that the magnitude of the reflection coefficients at the waveguide junctions will be nearly equal to one. Finally the attenuation of the reflected wave will be less at the frequency of point 2 because it is generally true that attenuation in any such system increases with increasing frequency. All these factors, considered jointly, might well serve to explain why

PROPAGATION ON A CHARGE - FREE HELIX

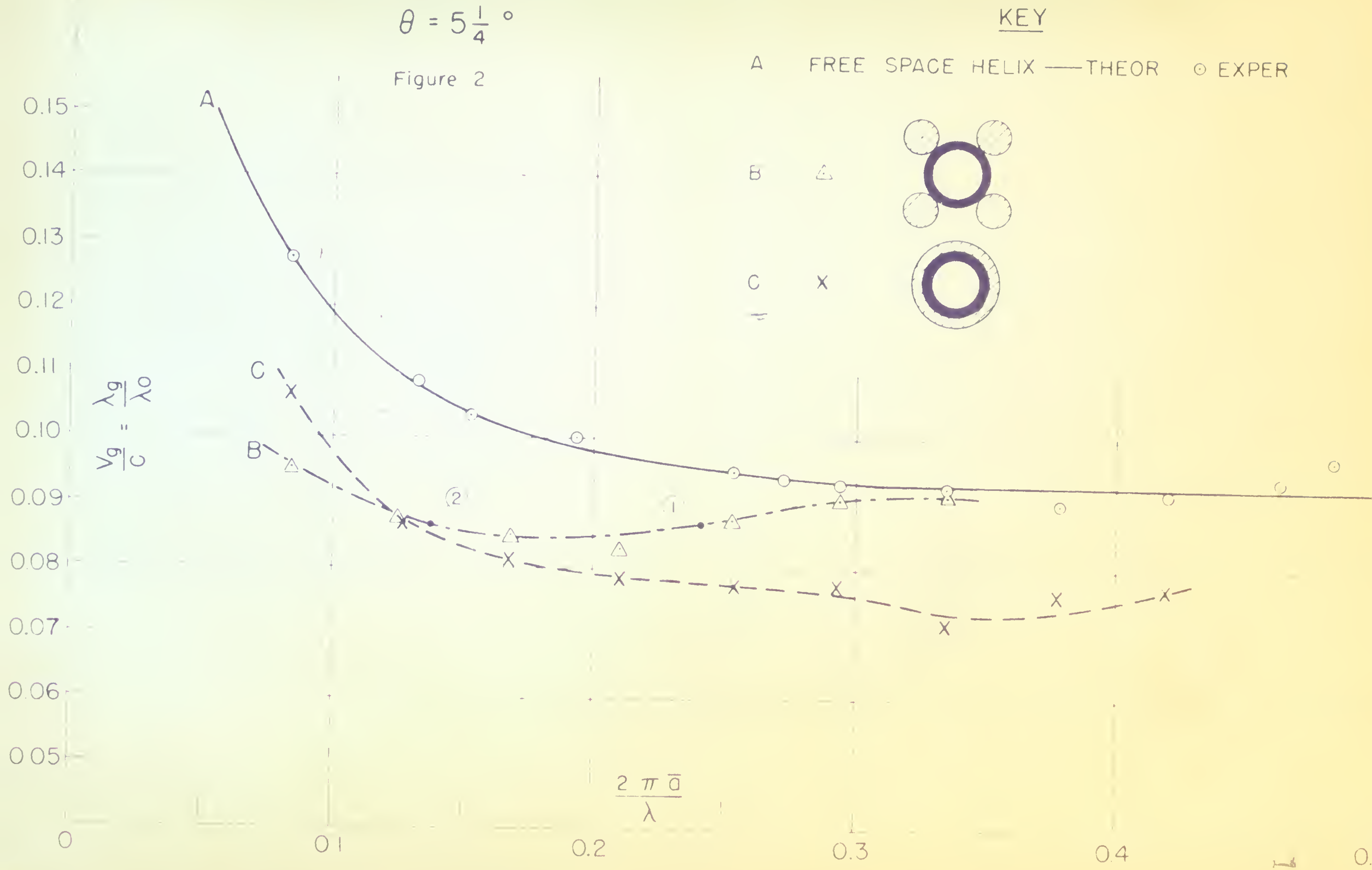


Figure 2

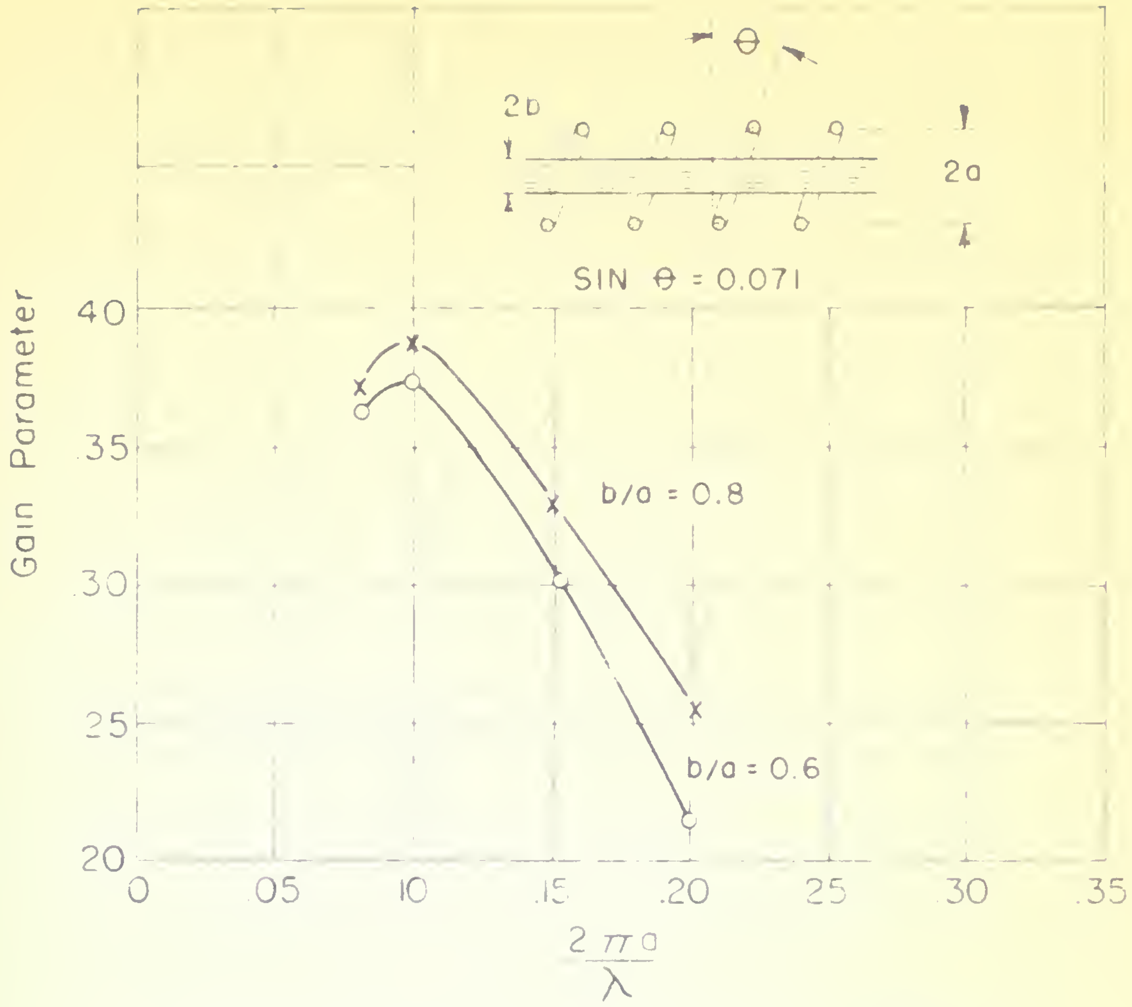


Figure 3

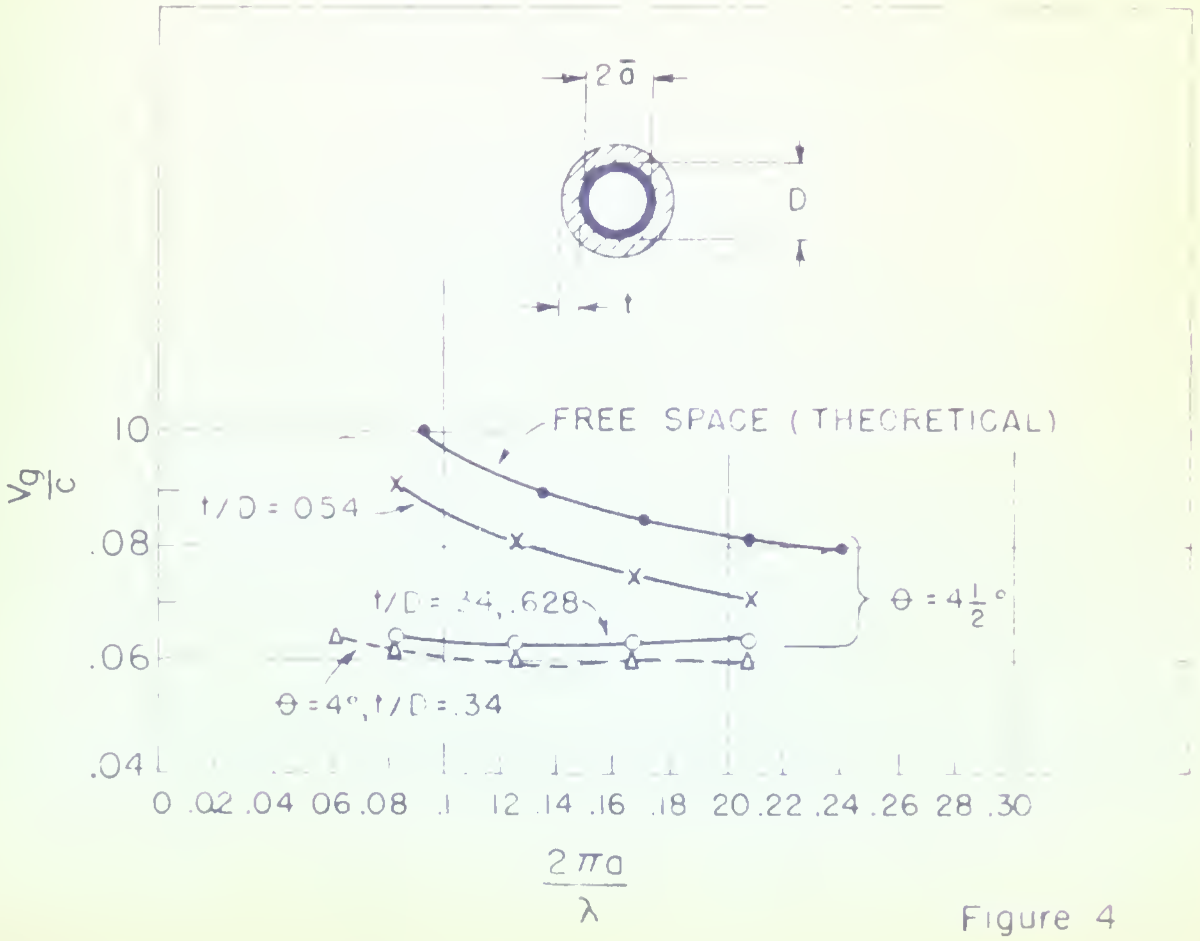


Figure 4

the earlier tubes oscillated at wavelengths somewhat longer than that of the signal.

Assuming that the above explanation is essentially correct, two procedures suggest themselves, each of which should result in increased stability. The first of these is to support the helix in such a way that the dispersive character of a helix in free space is retained. Curve C of Figure 2 indicates that this can be accomplished if the helix is supported by a thin dielectric shell. At 9000 megacycles per second it is impractical to use a thin shell because the relative wall thickness of glass tubing increases rapidly with decreasing bore. Figure 4 shows that for a thick dielectric shell the phase velocity curve in the frequency region of interest becomes flat, a situation which is just as bad as, if not worse than, the dip in the phase velocity curve of a helix supported by rods, see curve B, Figure 2. The second procedure is to resolve the question of helix support on the grounds of facility of construction while reducing the helix diameter so as to increase the gain per unit length in accordance with Figure 3. Under this scheme the maximum gain should occur at frequencies at which the waveguide junctions are fairly well matched. Since some gain should occur at frequencies outside the bandwidth of the junctions, this scheme requires that some lossy material be inserted along the helix to counteract the gain at these out-of-bandwidth frequencies, and make the tube stable. The

net result of this procedure should be an increase in the stable positive gain that could be realized. The tubes reported on herein were constructed in accordance with this second procedure.

A third design change from the former tubes consisted of increasing the number of helix turns per inch corresponding to the decrease in helix diameter. This was done so the tubes would operate at approximately the same accelerating voltage as the former tubes. Several other minor mechanical changes were necessary as a result of the principal changes enumerated above. Details of the actual construction, including the numerous difficulties encountered, are given in the next chapter.

net result of this procedure should be an increase in the static positive gain that could be realized. The tubes reported on herein were constructed in accordance with this second procedure.

A third design change from the former tubes consisted of increasing the number of helix turns per inch corresponding to the decrease in helix diameter. This was done so the tubes would operate at approximately the same accelerating voltage as the former tubes. Several other minor mechanical changes were necessary as a result of the principal changes enumerated above. Details of the actual construction, including the numerous difficulties encountered, are given in the next chapter.

CHAPTER II

CONSTRUCTION OF TUBES

Mechanical Problems.

A large number of mechanical problems were encountered in the construction of tubes which exhibited enough positive gain to make measurements of their performance worthwhile. In spite of experience gained with earlier tubes, the first six tubes constructed in this series were all failures. The mechanical problems were aggravated by the reduction in the helix diameter since this required that all parts become correspondingly smaller. The alignment problem was made worse by the omission of the dielectric rods, which had served to align the tube components in earlier tubes. Considerable progress was made in the solution of these problems but additional refinements in construction technique are still needed. Specific items which require more attention are discussed in Chapter IV.

Electron Gun.

The electron gun used in these tubes is of the Pierce type[11]. In order to expedite construction of the tubes it was decided to use an existing gun design, even though the gun itself had not been tested experimentally at the time construction work was started. The gun was designed by P. M. Lally closely following the techniques employed by L. A. Harris[12] in designing the gun used in the earlier

tubes of this program.

This gun was designed to give 5 ma of cathode current at 1500 volts. As a result of the earlier work it was expected that about 80% of this current would actually leave the gun. The first gun tested gave 2 ma of cathode current at 2000 volts of which only 0.4 ma left the gun. This poor performance was attributed to the fact that the hole in the anode was too small. This hole was enlarged from 0.035 inches to 0.070 inches and on the next test at 2000 volts the gun gave 2.0 ma of cathode current, of which 0.2 ma left the gun. This indicated that something was drastically wrong with the gun so another check was made on the design. It was discovered that in machining the cathode electrode on a profile cutter, no allowance had been made for the finite radius of the cutting tool. Thus, although the center of the tool followed the desired profile, the shape of the finished electrode was considerably in error. A new plot of the contour to be followed by the profile cutter was made, with due allowance for the radius of the tool. The next test showed a cathode current of 3.6 ma at 1500 volts of which 1.6 ma left the gun. The next modification attempted, in order to improve gun performance, was the replacement of the previous heater by a non-inductive type heater. This was done to prevent the heater magnetic field from interfering with the gun action. When tested at 2100 volts the gun then drew 6.0 ma of cathode current of which 3.5 ma left the gun. Cathode current fell to an unusably low value after this tube had been operated

only a short time. This was attributed to improper activation of the cathode with the new non-inductive heater, since the cathode was so enclosed that the emitting surface could not be seen during activation, and there was no way of knowing when the proper activation temperature had been reached. The gun was again modified by drilling holes in the cathode electrode, and by enlarging the existing holes in the gun sleeve. These holes served a twofold purpose by permitting direct viewing of the emitting surface during activation, and by permitting faster pumping of the inside of the gun. The latter feature was of importance because there was reason to believe that the small pumping channels originally provided were resulting in a certain amount of self-poisoning of the cathode during activation. After this final modification the gun drew 5.5 ma of cathode current at 2000 volts of which 3.0 ma left the gun. Although this was still considerably poorer performance than had been anticipated, the current available from the gun was now adequate for the problem at hand.

Helix.

The helix was formed by winding six-mil tungsten wire onto a smooth piece of 0.058 inch drill rod. The winding was performed by turning the rod in a lathe and feeding the wire onto the rod by means of a special jig fastened to the lathe carriage. The wire was kept under about 40 pounds tension during the winding. Immediately after winding, while

the wire was still under tension, the ends were securely clamped. The helix and rod were then fired at about 750° C for about 5 minutes in an atmosphere of hydrogen. About half of the helices became so brittle that they broke very easily and could not be removed from the rods. Even after the others had been removed from the rods there was still the problem of pulling out the ends to form the transition section between the matching slug and the main portion of the helix. It was found that a better procedure was to form the transition section before the helix was fired, and this method was finally used. The first helices were wound at 64 turns per inch with the result that interaction took place at beam voltages of 1200 to 1300 volts. This was later changed to 46 turns per inch so that interaction would take place at between 1800 and 1900 volts, which corresponded to a better range of operation for the gun. After the helix had been prepared, it was inserted into a glass tube which was to serve as its support in the finished tube, and the assembly was examined under a toolmaker's microscope for uniformity of pitch. If this examination revealed that the helix pitch was uniform to ± 1%, the helix was ready for insertion in the tube.

Dielectric Shell.

The dielectric shell used to support the helix consists simply of a glass tube which is centered in the envelope by spacers. In the first few tubes no intentional loss was

added to reduce the tendency of the tubes to oscillate. Since oscillations did occur it was necessary to put in some added loss. The insertion loss of a helix with its matching slugs was measured as 16 db. Painting about one inch of the outside of the glass shell with Aquadag increased this insertion loss to 23 db. Increasing the length of this painted section had no further effect on the insertion loss. Since this amount of loss did not appear to be adequate, a section one-half inch long of the inside of the shell was painted with Aquadag which increased the insertion loss to 35 db. This painting was accomplished by squirting the Aquadag inside the shell with a long eyedropper, and then washing away the excess by dipping the shell vertically into a beaker of water. None of the tubes treated in this manner showed any signs of oscillating.

R-F Coupling.

There are a number of requirements on the arrangements used to couple r-f power into and out of the tube. They should be simple enough so that the tube can be inserted into or removed from an r-f line at will. They should be broadband in order that the tube be broadband, and also in order to minimize the reflections which cause oscillations. They should excite principally the required slow mode of propagation on the helix, and a minimum of the fast modes which the helix is also capable of supporting. Their radiation into space should be a minimum so that standing-wave measurements in the input or output line will be a true indication of the

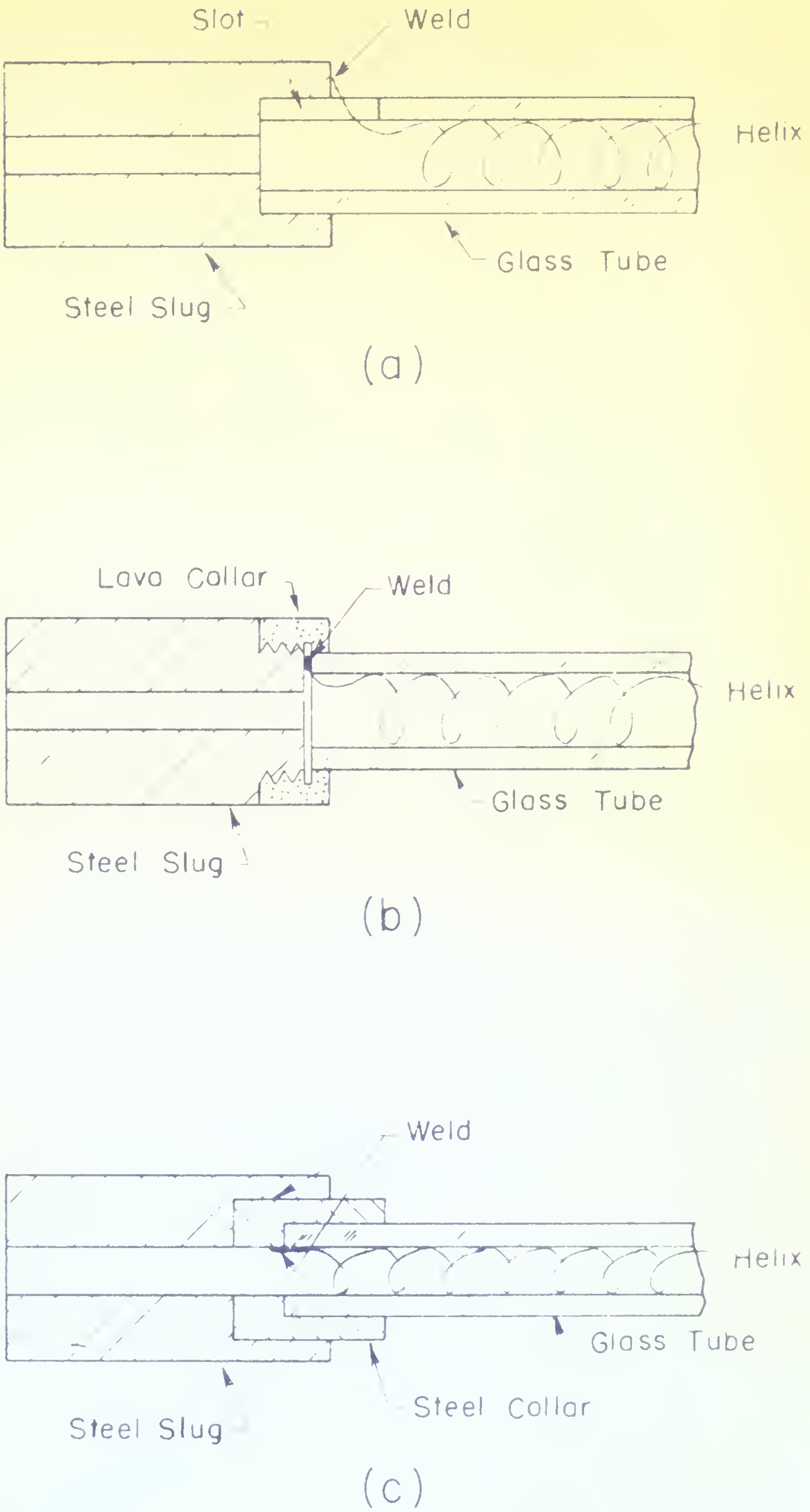
amount of coupling. Finally, any additional parts involved in providing the coupling should be held in place rigidly enough so that they are unable to move about and thus upset the uniformity of the helix pitch.

The coupling used in these tubes is patterned after an arrangement first used at the Bell Telephone Laboratories[9]. Considerable time and effort was devoted to an attempt to design the slugs so that the assembly of slugs, helix, and inner glass tube would form a rigid structure. The various types of slugs tried are shown in Figure 5. Of these (a) was discarded because of the difficulty of cutting the slot in the glass tube through which the helix wire was to be led in order to weld the wire to the slug. The type shown in (b) was discarded because the helix wire was too brittle to be formed into the sharp bend at the point where the wire was to be welded to the slug. The one shown in (c) was discarded because it proved to be rather narrow band and also too sensitive to the position of the tube in the waveguide section. After this series of attempts the requirement that the slugs and the inner glass tube form a rigid assembly was abandoned, and it was decided to design in such a manner that the gun and the collector assembly would push against the slugs and thus hold them in place.

All the measurements of the matching properties of the slugs mentioned above were made by simply plotting the VSWR at several frequencies as a function of the slug position, which was carefully measured by means of a depth gauge. This amount of clamping. Finally, any additional parts involved in positioning the mounting should be held in place rigidly enough so that they are unable to move around and thus change the uniformity of the field lines.

The mounting used in these tests is patterned after an arrangement first used at the Bell Telephone Laboratories[9]. Essentially this arrangement was intended to be an attempt to design the clamps so that the assembly of clamps, bolts, and lower plates would form a rigid structure. The various types of clamps tried are shown in Figure 5. Of these (a) was discarded because of the difficulty of cutting the slot in the glass tube through which the bolts were to be led in order to hold the tube to the clamp. The type shown in (b) was discarded because the bolts were too brittle to be screwed into the glass tube at the point where the tube was to be clamped to the ring. The one shown in (c) was discarded because it proved to be rather difficult to make and also not sensitive to the position of the tube in the compression section. After this series of attempts the requirement that the clamps and the inner glass tube form a rigid assembly was abandoned, and it was decided to design the clamps in such a manner that the gap and the adjacent assembly would push against the clamps and thus hold them in place.

All the measurements of the damping properties of the clamps mentioned above were made by simply vibrating the reed at several frequencies as a function of the clamp position, which was carefully measured by means of a depth gauge. This

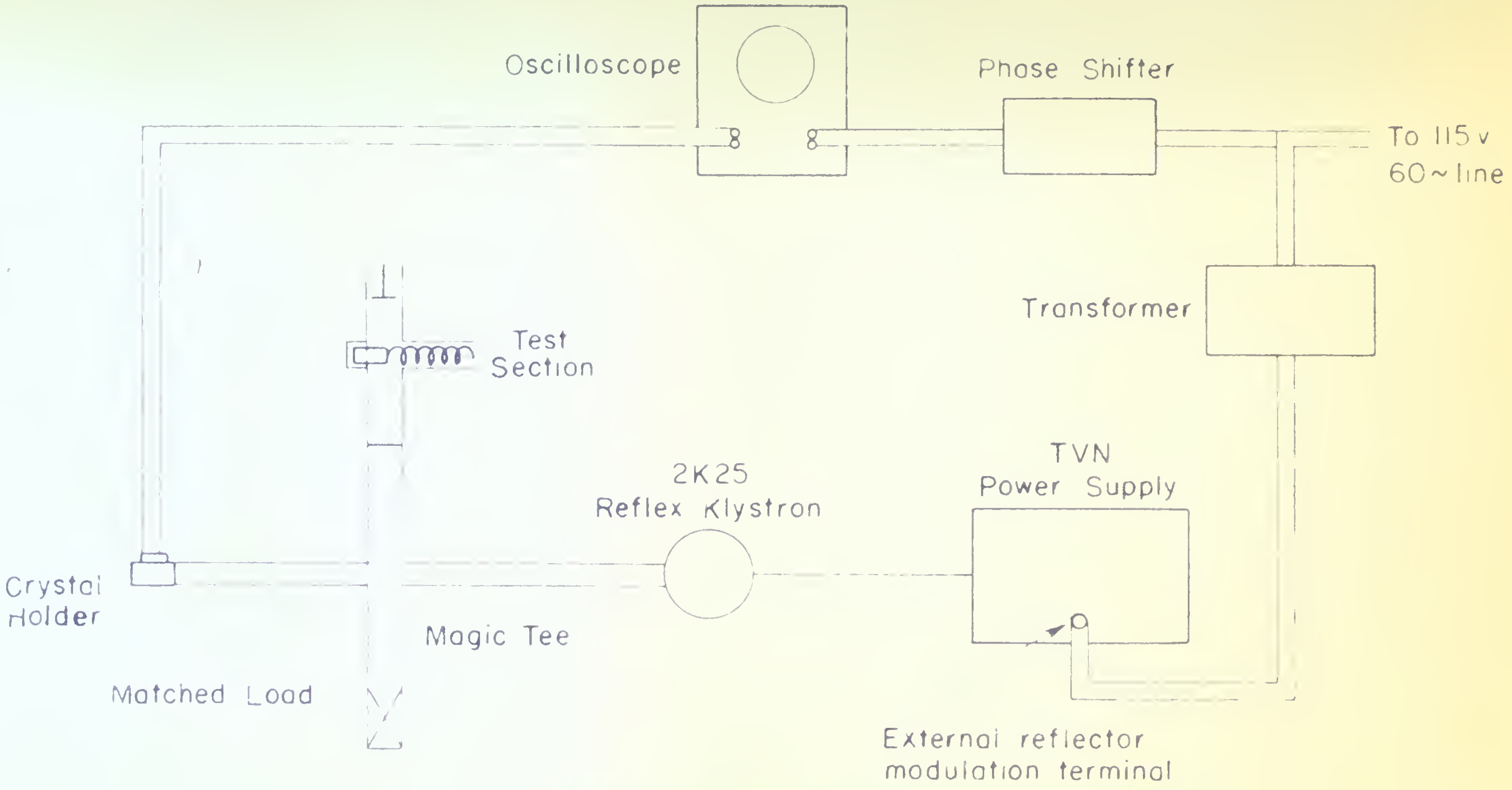


VARIOUS METHODS PROPOSED for OBTAINING MECHANICAL RIGIDITY between MATCHING SLUG and INNER GLASS TUBE

Figure 5

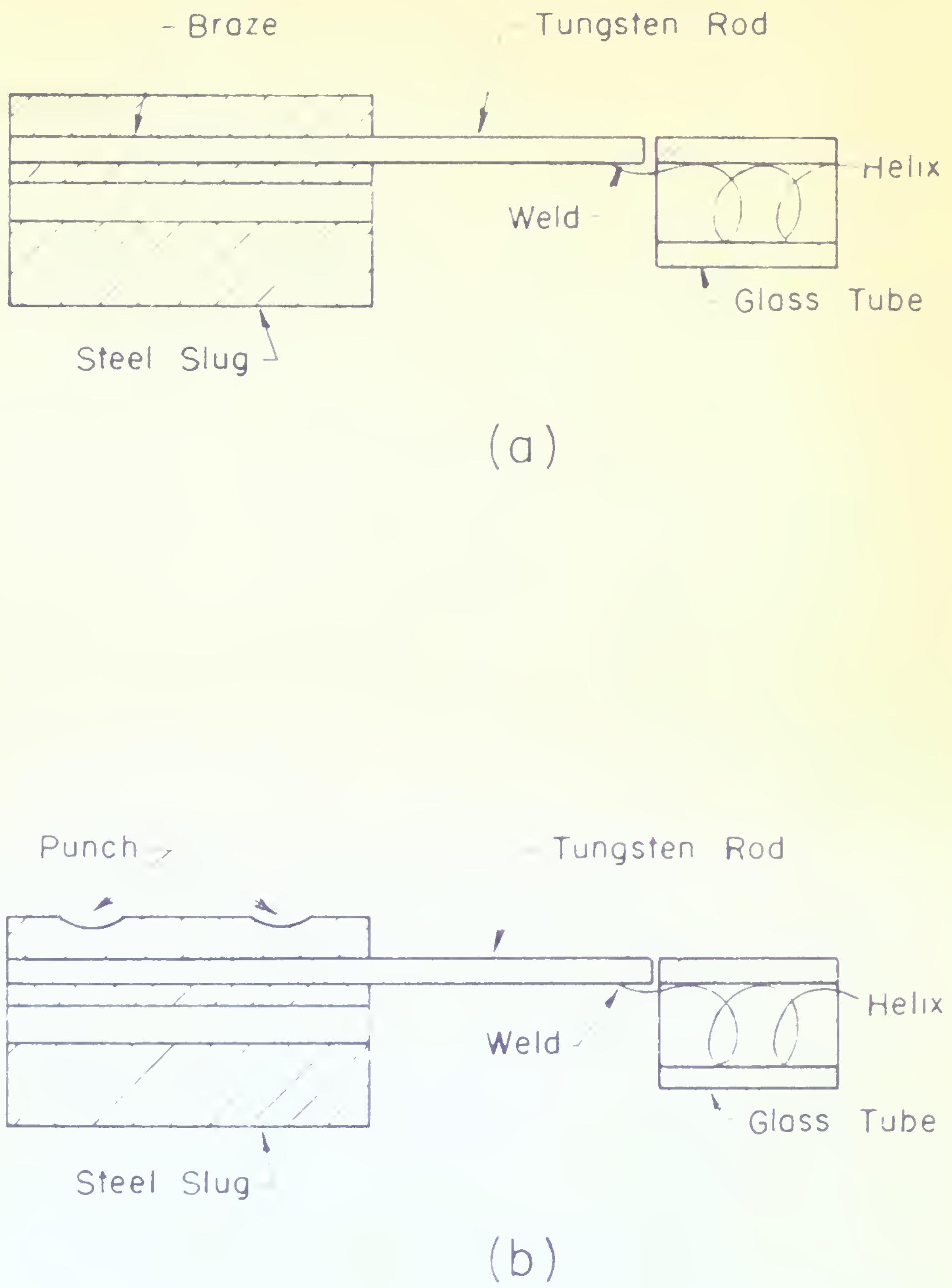
method proved to be very tedious and the results were not at all consistent. A much quicker method of checking the matching qualities of a slug was then devised using the set-up shown in Figure 6. Here a frequency modulated signal was introduced into a magic tee. One arm of the tee was terminated in a flat load, another arm was terminated with the waveguide section in which the slug under test was placed, and the remaining arm was terminated in a crystal holder. The output from the crystal was placed on the vertical deflection plates of a cathode ray oscilloscope. The horizontal sweep was driven by the same voltage used to produce the frequency modulated signal. In this way the slug could be quickly placed in the position which gave the minimum vertical deflection on the oscilloscope, and the effect of small changes in slug position could be quickly determined.

The first slug tested in this manner and used in the first few tubes is shown in Figure 7 (a). This seemed to have good frequency and positional characteristics but was eventually discarded for the following reasons. In the first place, it could not be made in one piece but had to be made in two pieces. The two pieces could not be welded together so an attempt was made to hard solder them. Since the slug itself was made of stainless steel and the post was made of tungsten, it was first necessary to put a light nickel plate on the two pieces in order to do the hard soldering. This entire procedure was so clumsy that it was abandoned and another method was tried which involved using a center punch



SET-UP for QUICKLY TESTING MATCH at WAVEGUIDE JUNCTION

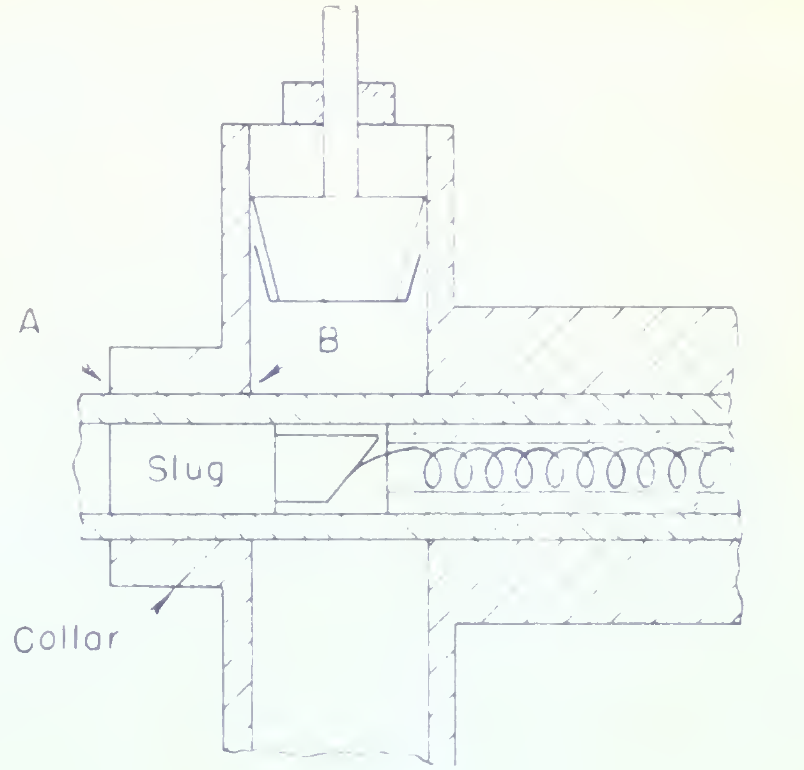
Figure 6



ROD TYPE SLUG

Figure 7

to force the side of the slug down on the post as shown in Figure 7 (b). This too was abandoned because the punch marks deformed the side of the slug so that it was no longer a good fit in the envelope. In the second place, this type slug was also poor electrically. An understanding of this defect requires first that an explanation be made of the choke which is provided to reduce radiation into space. Figure 8 shows how this choke is formed. It consists of a quarter-wave section of coaxial line terminated in an open circuit. The coaxial line is made up of the slug as an inner conductor, a ring soldered on the waveguide as an outer conductor, and the tube envelope as a glass dielectric. The choke action is that the open circuit at point A, Figure 8, is reflected back as a short circuit at point B

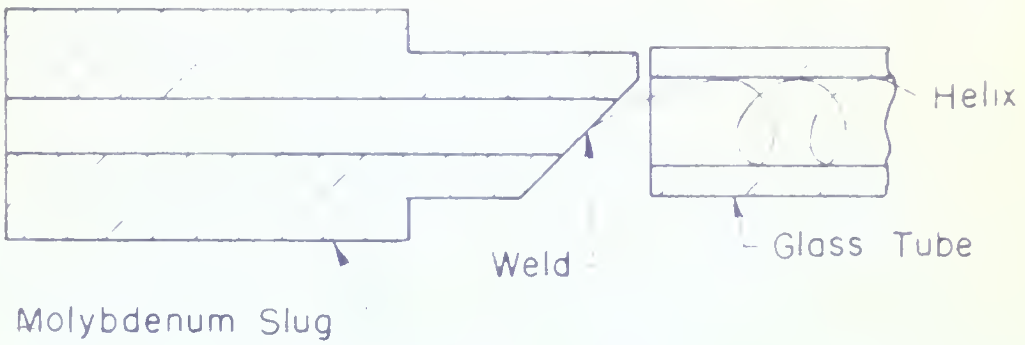


WAVEGUIDE JUNCTION SHOWING CHOKE

Figure 8

so that the waveguide acts as though the hole in its side were not present. Considerations of mechanical strength made it necessary that the diameter of the envelope be so large that the coaxial line formed by the slug and the ring was capable of propagating not only the TEM wave but also the TE_{11} wave. The non-symmetry of the slug with its post on one side excited the TE_{11} wave in the choke to a considerable extent. As a result the choking action was so poor that the power radiated into space was only about 5-8 db below the power incident on the junction. This meant that with the slug adjusted for a good match it was no indication that all the incident power was actually being transmitted onto the helix.

The type of slug that was finally adopted is shown in Figure 9. With this type the radiated power is about 20 db



FINAL SLUG DESIGN

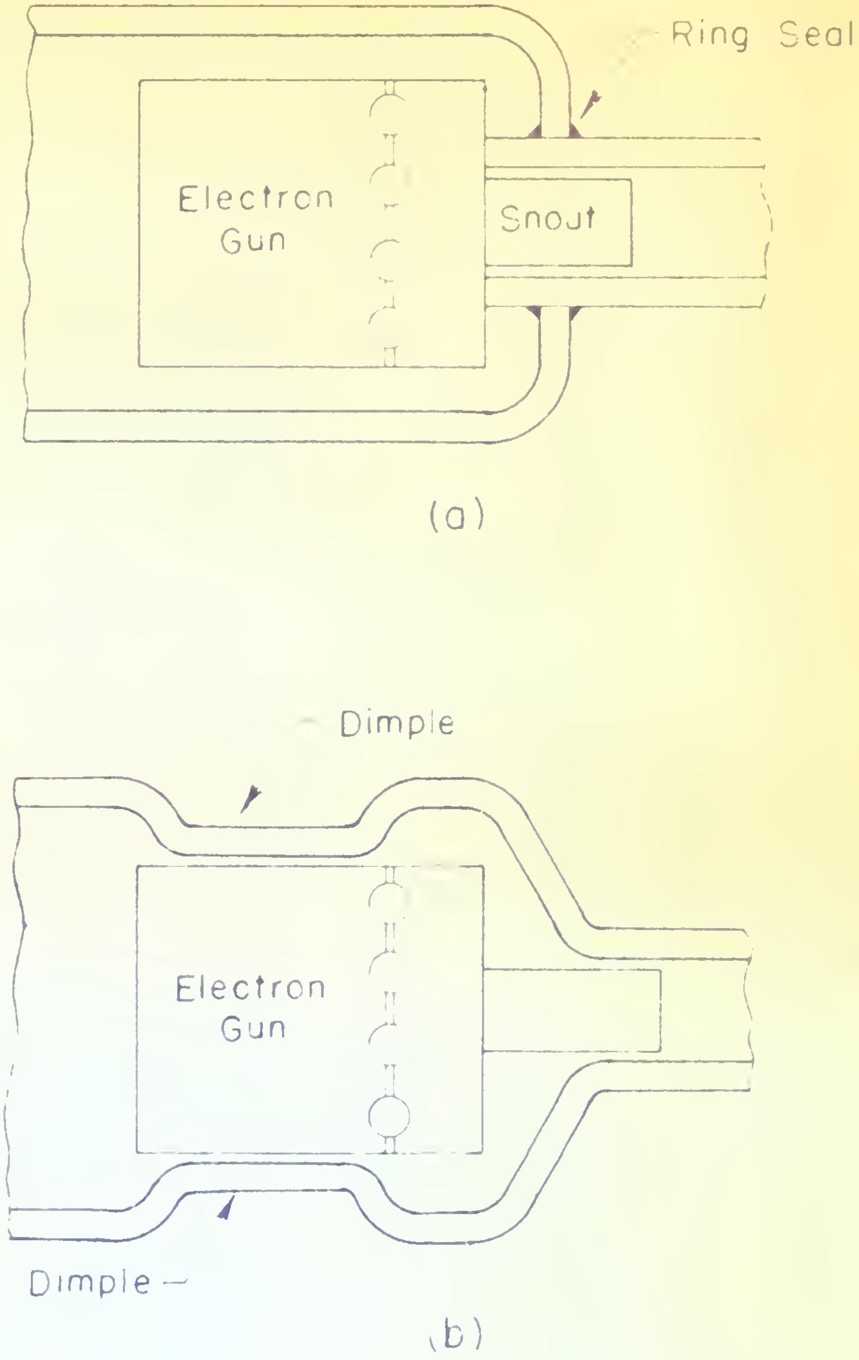
Figure 9

below the power incident on the junction and the junction exhibits a reasonably good match (VSWR less than 2.5 between 3.1 and 3.4 cm.). The match realizeable with this slug is not too sensitive to the position of the tube. Finally, a slug of this type is machinable in one piece, and there is no necessity for any clumsy brazing operation or any deforming punching operation.

Envelope and Alignment.

The omission of the dielectric rods which had served to align the components of the previous tubes made it necessary that the alignment be provided by the envelope itself. The precision of alignment necessary to direct a beam of electrons through a helix 8.75 inches long and having an inside diameter of 0.058 inches required that the tube parts be constructed with quite small tolerances. In fact, the problem was not fully appreciated at first but became apparent as experience was gained in the construction of the tubes. Even then, in spite of using the greatest care in keeping the tolerances as small as possible, only a fair amount of success was obtained, in that at best only about 60% of the current leaving the gun arrived at the collector.

A basic difficulty encountered in making the envelopes was the non-uniformity of the commercially available glass tubing. This was aggravated by the necessity for providing sufficient clearance between glass and metal parts to allow for expansion of the metal during the "bake-out" and during operation. The first envelope design used is shown in



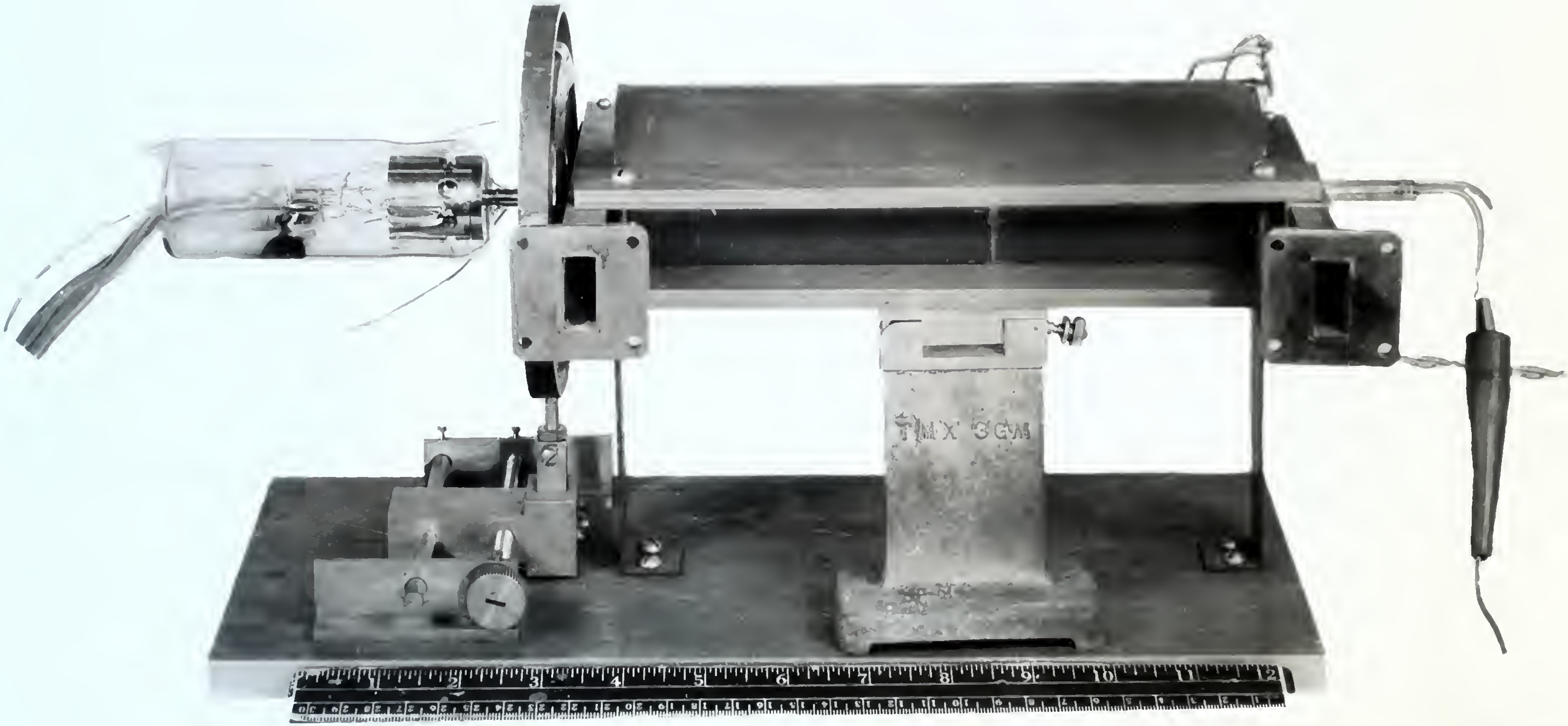
METHODS USED for ALIGNING ELECTRON GUN in ENVELOPE

Figure 10

Figure 10 (a). Here the snout on the gun, projecting into the small section of the envelope, was supposed to hold the gun in the proper alignment. The first tube of this type had too close a fit between the gun snout and the glass with the result that the tube cracked at the ring seal during "bake-out". When another tube was built with enough clearance for expansion, the gun was out of line and also free to wobble. As a result of the gun's being out of line most of the current flowed to the slug instead of proceeding down the helix. As a result of the gun wobble, the cathode lead, although properly welded to the cathode, simply pulled out a portion of the cathode wall causing an open circuit in the tube. Both of these problems were solved by changing the envelope to the design shown in Figure 10 (b). Here the envelope was dimpled onto a special hard carbon jig with the dimples placed so that principal support for the gun was located near the rear portion of the gun. In this manner it was possible to achieve good alignment and still provide the clearance necessary to allow for expansion.

Focusing.

A longitudinal magnetic field, supplied by a long solenoid into which the tube was inserted, served to keep the beam from diverging due to space charge forces within the beam. This arrangement is conventional for traveling-wave tubes. Experience showed, however, that the field of this long solenoid did not extend closely enough to the



Traveling-Wave Tube Including Waveguide Junctions and Focusing Coils

Figure 11

gun so that there was appreciable divergence of the beam even before it passed through the first slug. To overcome this it was necessary to provide an additional lens right in front of the gun, as shown in Figure 11. This lens prevented the beam from diverging initially, but at the same time the field from the lens extended into the gun and upset the electrostatic focusing of the beam inside the gun. The best results were obtained by making the face of the lens near the gun of a magnetic material, steel, while the other face was made of brass. This arrangement provided a continuity of magnetic field between the lens and the main solenoid, and at the same time shielded the gun from the magnetic field. With this combination it was possible to collect about 1.5 ma. of current on the collecter out of a total of 2.5 ma. leaving the gun.

CHAPTER III

MEASUREMENTS

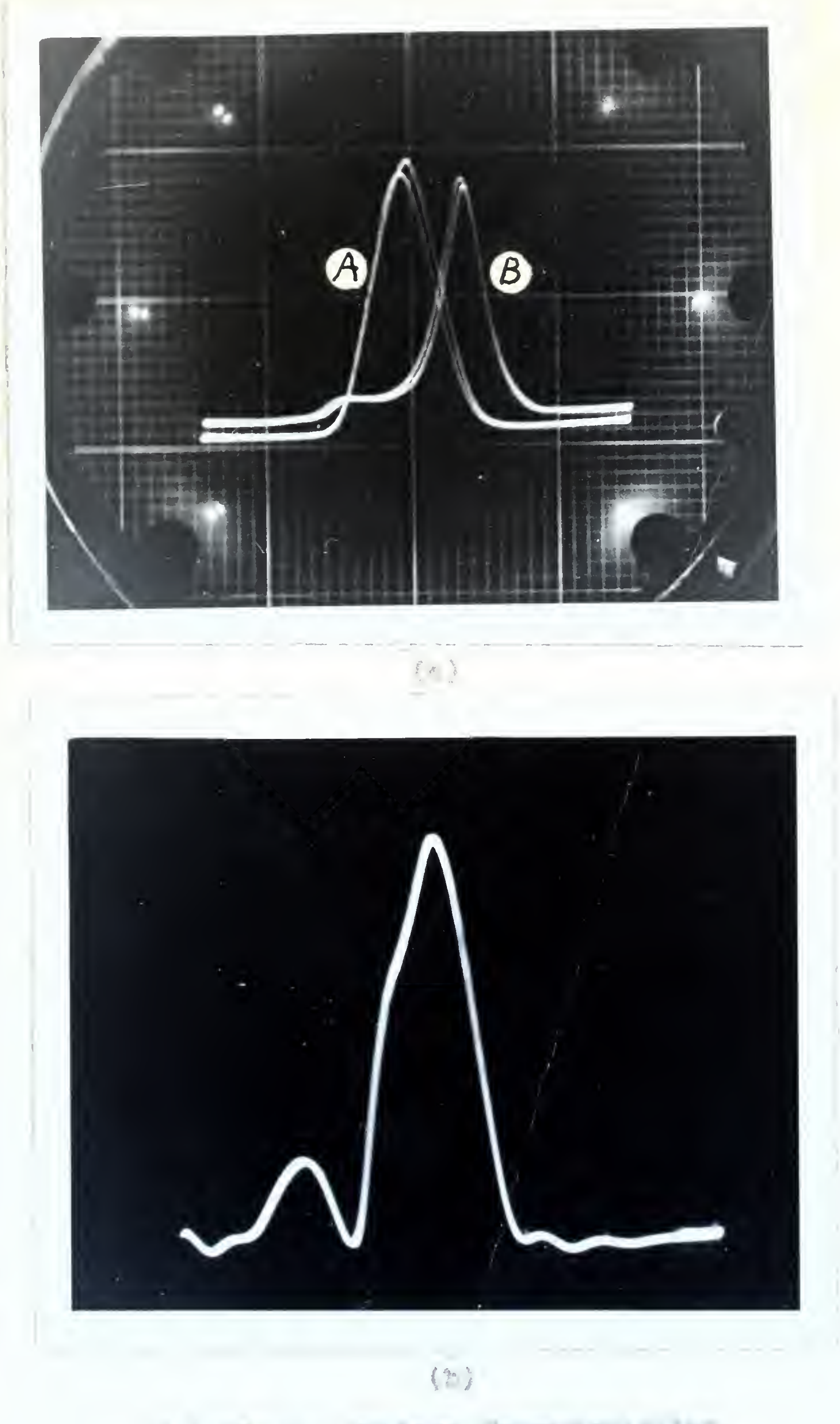
General Information.

A total of eight tubes were built in this series. A limited amount of data was obtained from tube 4 up to the time it became unusable due to an open circuit at the cathode. Most of the measurements were made on tube 7, although enough data were obtained on tube 8 to indicate good correspondence between these two. All the others were complete failures.

Effect of Voltage on Gain.

At a fixed frequency the gain versus beam voltage characteristic is readily obtained. A 60 cycle voltage is used to sweep the beam voltage about the point of maximum gain, and also to provide the horizontal sweep of a cathode ray oscilloscope. By applying the rectified output of the tube to the vertical deflection plates, the gain versus voltage characteristic may be viewed directly on the oscilloscope.

The oscillograms shown in Figure 12 were obtained in this manner. The curves of Figure 12 (a) apply to tube 7 of this series. Here curve A was obtained at an input power of about one microwatt, while curve B was obtained at an input power of about 25 mw. For both these curves the horizontal sweep represents a 600 volt change in beam voltage. The vertical scale was not calibrated, but it was necessary to introduce about 30 db loss ahead of the crystal in order to reduce curve B to approximately the same height as curve A



(a)

(b)

Gain Versus Voltage Characteristics

Figure 22

on the oscilloscope. Comparison of these curves indicates that the voltage of optimum gain is about 80 volts higher at the higher level of input power. Although it is not shown in Figure 12, it was noted during the course of these measurements that there is no appreciable change in the voltage of optimum gain until the input power exceeds about 5 mw.

There is a significant difference between the low-level characteristic of tube 7, curve A Figure 12 (a), and the corresponding characteristics observed by other investigators. This difference is apparent by comparison with Figure 12 (b), which applies to one of the earlier tubes of this program. Notice the wiggles on either side of the principal gain peak of this curve. These wiggles are predicted by the small-signal theory as the result of interference between the three forward waves which can exist in the presence of an electron beam. Theoretical gain vs. voltage characteristics showing this interference effect have been plotted[4]. This effect has invariably been present in the characteristics of other tubes, even including the short-lived tube 4 of this series. The wiggles are not present, however, in the tube 7 characteristic, nor in the tube 8 characteristic, which is not shown. This must be due to the nature and location of the lossy section built into tubes 7 and 8, since the principal difference between them and tube 4 is that the latter did not have any lossy section. The absence of an interference pattern cannot be explained simply by the fact that a lossy section was included in tubes 7 and 8. The tube which yielded Figure 12 (b)

also had a lossy section, but it was of a different form. There the lossy material was painted on the four ceramic rods used to support the helix, and the loss was therefore discontinuous around the helix periphery. In tubes 7 and 8 the loss is continuous around the helix periphery. Furthermore, in these latter tubes the lossy section is somewhat nearer the input end, whereas in the earlier tube it was located midway along the helix. One or both of these differences must be responsible either for a more complete attenuation of the non-growing waves, or for a decreased excitation of them in the portion of the helix following the loss.

We turn now to the curve of optimum beam voltage as a function of frequency for low-level operation. According to the theory, this curve should be of the same form as the curve of phase velocity versus frequency, see Figures 2 and 4. The available oscillator covers a bandwidth of about 1200 megacycles per second, which is only about 15% of the nominal operating frequency. Measurements were made which indicate that the beam voltage versus frequency curve is flat over the operating range of frequencies covered by the oscillator. This is shown in Figure 13, which also shows the effect of helix pitch on optimum beam voltage. In the case of tube 4, which did not have any lossy section, some additional points were obtained by measuring the oscillation wavelength. There is good correspondence between the form of the curves of Figure 13 and those of Figures 2 and 4.

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We turn now to the curve of optimum beam voltage as a function of frequency for low-level operation. According to the theory, this curve should be of the same form as the curve of phase velocity versus frequency, see Figures 3 and 4. The available oscillator covers a bandwidth of about 1500 megacycles per second, which is only about 15% of the nominal operating frequency. Measurements were made which indicate that the beam voltage versus frequency curve is flat over the operating range of frequencies covered by the oscillator. This is shown in Figure 13, which also shows the effect of helix pitch on optimum beam voltage. In the case of tube 4, which did not have any lossy section, some additional points were obtained by measuring the oscillation wavelength. There is good correspondence between the form of the curves of Figure 13 and those of Figures 3 and 4.

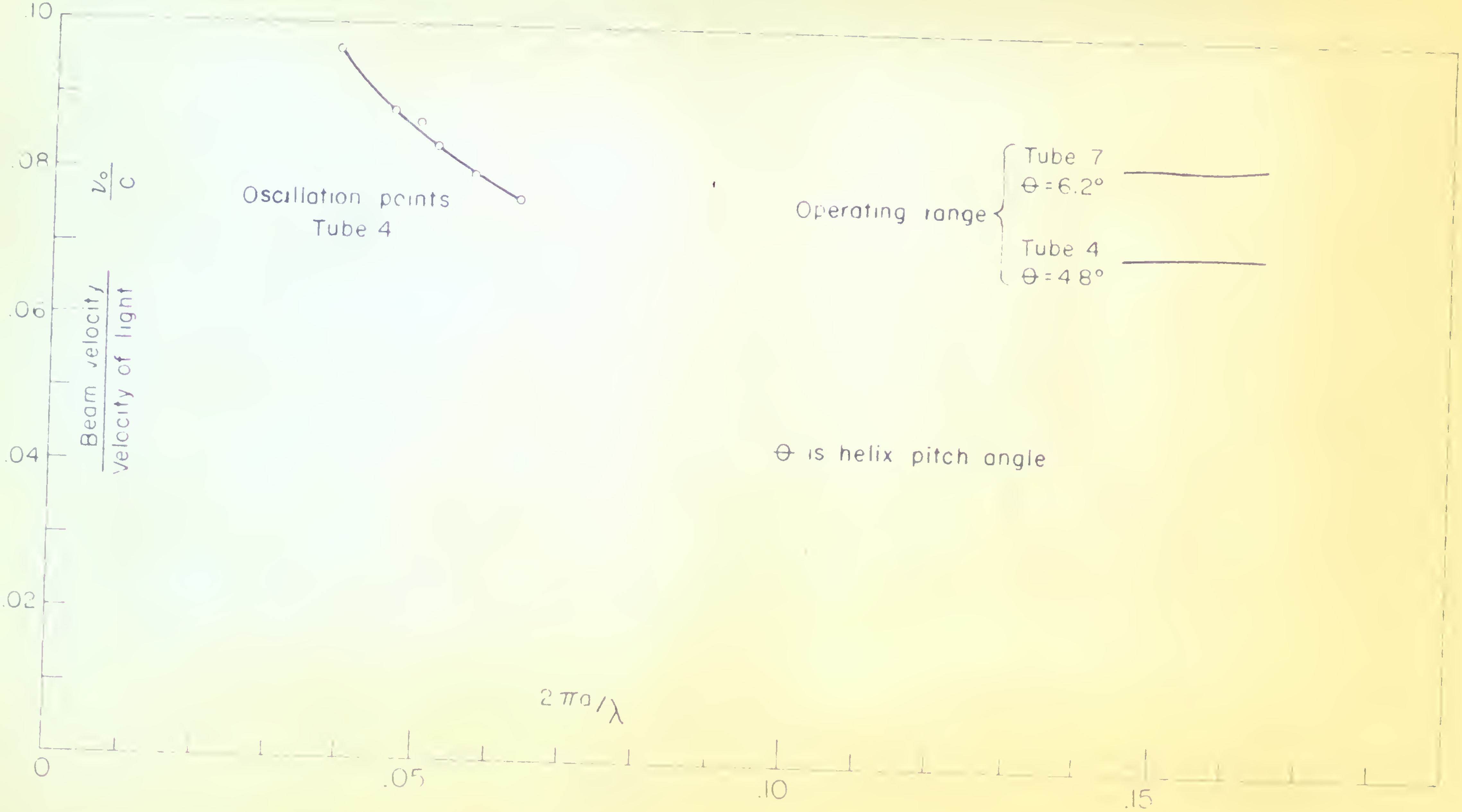
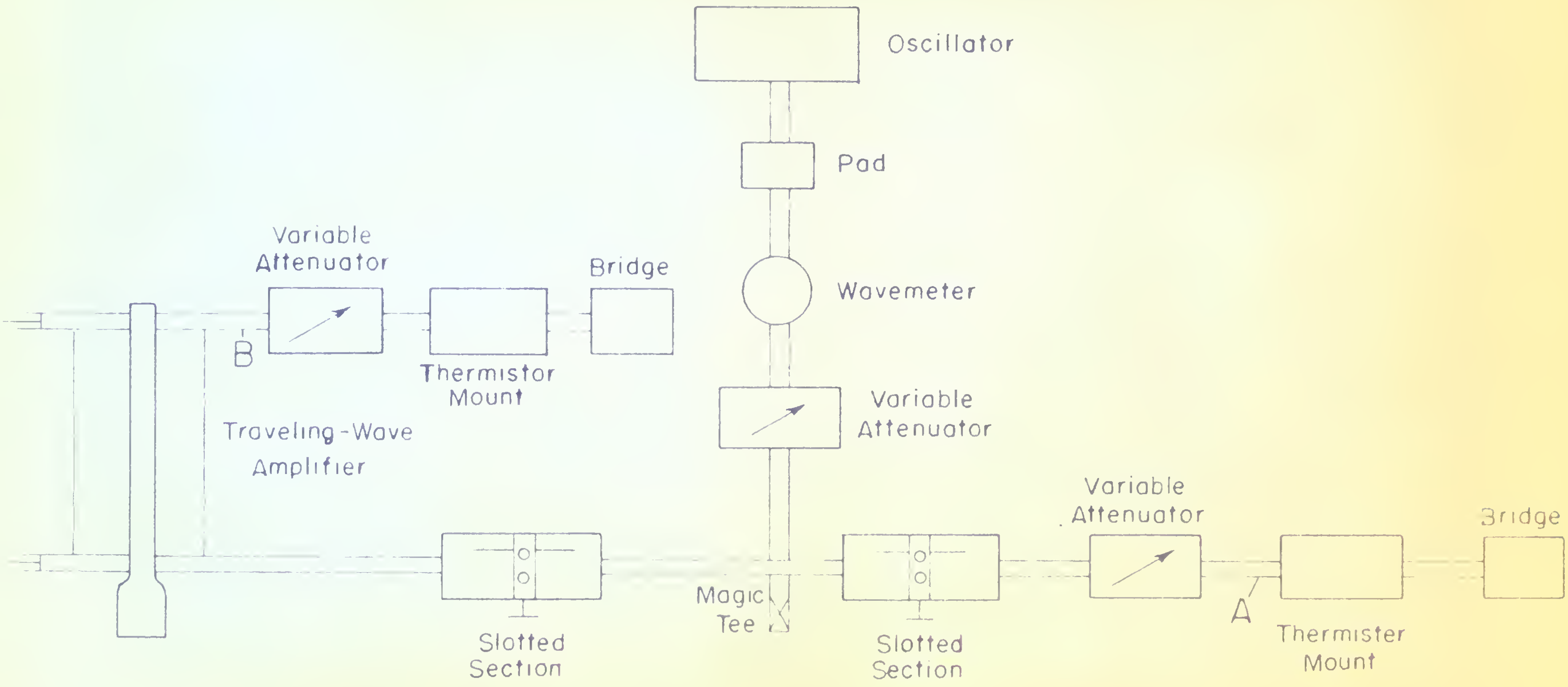


Figure 13
OPTIMUM BEAM VOLTAGE as a FUNCTION of FREQUENCY

Power Output and Gain at a Fixed Frequency.

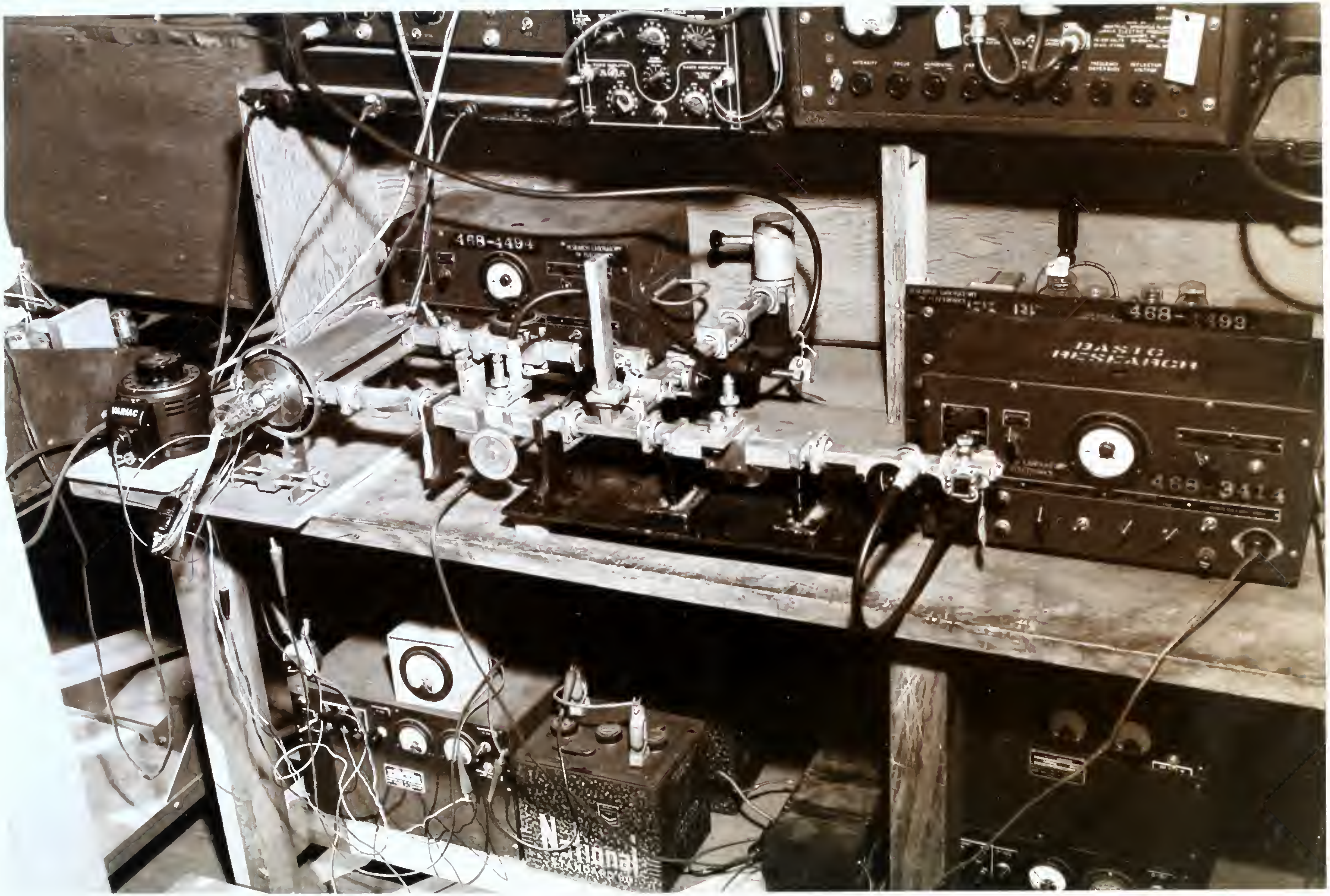
The set-up used for making these measurements is shown schematically in Figure 14, and photographically in Figure 15. Power from the oscillator is fed into a magic tee where it divides equally between two of the arms. One of these arms is connected to a thermistor mount at point A, Figure 14, while the other is connected to the input of the traveling-wave amplifier. A slotted section is essential on the amplifier side of the tee to adjust the match at the waveguide junction. The output of the amplifier is connected to a second thermistor mount at point B, Figure 14. Calibrated attenuators, placed in front of each thermistor mount, permit operating each mount, with its associated bridge, in the range of best accuracy. Before any measurements were made the amplifier was replaced by the second thermistor mount and measurements were made to verify that the same amount of power was actually coming out of each arm of the tee. The set-up was then reassembled and measurements made by simply varying the power entering the magic tee, and reading the input and output directly on the bridges.

The results are shown in the curves of Figure 16. Actually, the gain is nearly constant for input power levels of about 100 microwatts or less, but the gain falls off quite rapidly as the tube becomes saturated. A highly saturated region is finally reached where an increase in the input power causes a decrease in the output power. Note that the beam voltage was maintained at the optimum value for low-level gain throughout these measurements. This is



SET-UP for MEASURING GAIN and OUTPUT POWER vs. INPUT POWER

Figure 14



Set-up for Measuring Gain and Power Using Two Thermistors

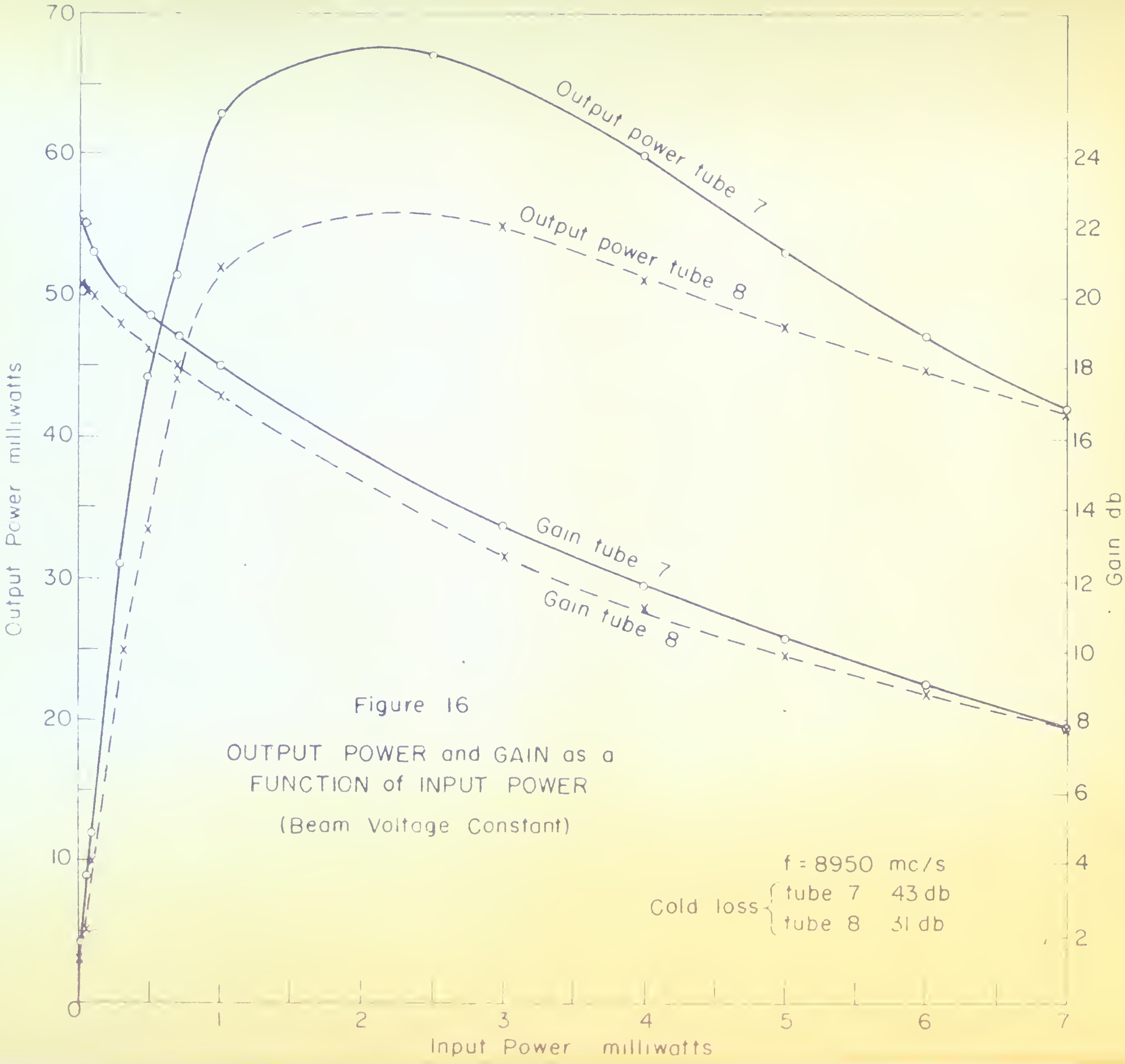


Figure 16

OUTPUT POWER and GAIN as a FUNCTION of INPUT POWER

(Beam Voltage Constant)

f = 8950 mc/s

Cold loss { tube 7 43 db
tube 8 31 db

in accordance with the conditions which would prevail if the tube were to be used as a low-level amplifier. It was pointed out in the preceding section that the voltage of optimum gain does not change appreciably until the input power exceeds about 5 mw. Note that the maximum power output corresponds to an input power of about 2.5 mw. Therefore, we are justified in comparing the measured maximum power output with the theoretical maximum power output which is calculated below.

Since there are many factors that are not known, and since the theory is only approximate, our calculation can hardly be more than a good guess. We expect, however, that our comparison will show correspondence at least as to order of magnitude. This computation is in accordance with the procedure outlined by Pierce[2]. We start with the known conditions of tube operation which are, in Pierce's notation,

V_0 = 1850 volts,

I_0 = 2.0 ma (this is a compromise value arrived at from the measured values of helix current = 1.0 ma and collector current = 1.5 ma),

$\omega = 5.63 \times 10^{10}$ rad./sec.,

$\beta_0 = \frac{\omega}{c} = 1.87 \times 10^{2}$ rad./meter, and

a = 0.032 inches.

We assume that the helix is lossless, and that the tube is operated at synchronous velocity.

Then $\gamma = \beta = \dfrac{\omega}{u_0} = \dfrac{\omega}{\sqrt{2\eta V_0}} = \dfrac{5.63 \times 10^{10}}{\sqrt{2(1.759 \times 10^{11})(1850)}}$

$= 2.2 \times 10^3$ rad./meter.

$\gamma a = (2.2 \times 10^3)(0.032)(0.0254) = 1.79.$

From the curve of $F(\gamma a)$ vs. γa, we find that $F(\gamma a) = 2.3$.

Now $C = \left(\dfrac{\beta}{\beta_0}\right)^{\frac{1}{3}} \left(\dfrac{\gamma}{\beta}\right)^{\frac{4}{3}} F(\gamma a)\left(\dfrac{I_0}{4V_0}\right)^{\frac{1}{3}}$

$= \left(\dfrac{22 \times 10^2}{1.87 \times 10^2}\right)^{\frac{1}{3}} (1)^{\frac{4}{3}} (2.3)\left(\dfrac{2.0 \times 10^{-3}}{4(1850)}\right)^{\frac{1}{3}}$

$= 0.027$

And $P = \dfrac{I_0 V_0 C}{2} = \dfrac{(2.0 \times 10^{-3})(1850)(0.027)}{2} = 5 \times 10^{-2}$

watts. Thus the computed value is 50 mw as compared to the measured value of 67 mw. This correspondence is better than we might expect and indicated that there must be some mutual cancellation between the factors which could not be accurately taken into consideration.

Bandwidth.

Measurements of gain versus frequency, in order to establish the bandwidth, proved to be the most difficult and tedious. Two different methods were employed which gave reasonably similar results. The difficulty arose from the fact that the bandwidth of the amplifier is much greater than the bandwidth of various other elements, such as attenuators and thermistor mounts, which were used in making the measurements. The first method made use of the same set-up

described above for measuring power. Figures 17 and 18 show the results of two sets of measurements. Each set was made at input power levels of 25 and 100 microwatts. The other method employed is a slight modification of the basic set-up shown in Figure 14. Here the two thermistor mounts are removed and the input and output powers are compared by means of a spectrum analyzer. The procedure used is as follows. Power from the magic tee, equal to the input power to the tube, is fed into the spectrum analyzer by connecting a waveguide-to-coaxial line transition at point A, Figure 14. A pad attenuator is used in front of the transition to prevent the transition from disturbing the power division in the magic tee. The pip on the spectrum analyzer is then set at a convenient level. Point A is then terminated in a flat load and the waveguide-to-coaxial line transition, with pad attenuator attached, is shifted to the output of the amplifier, Point B, Figure 14. The calibrated attenuator, which is part of the spectrum analyzer, is then adjusted to reduce the pip to its original level. The change in the setting of this attenuator gives the gain in db directly. These results are shown in Figure 19.

The scattering of the points of Figures 17 and 18 is probably due to the frequency characteristics of the thermistor mounts. There is considerably less scattering of the points in Figure 19. If we ignore the scattering there is reasonably good correspondence between the data ob-

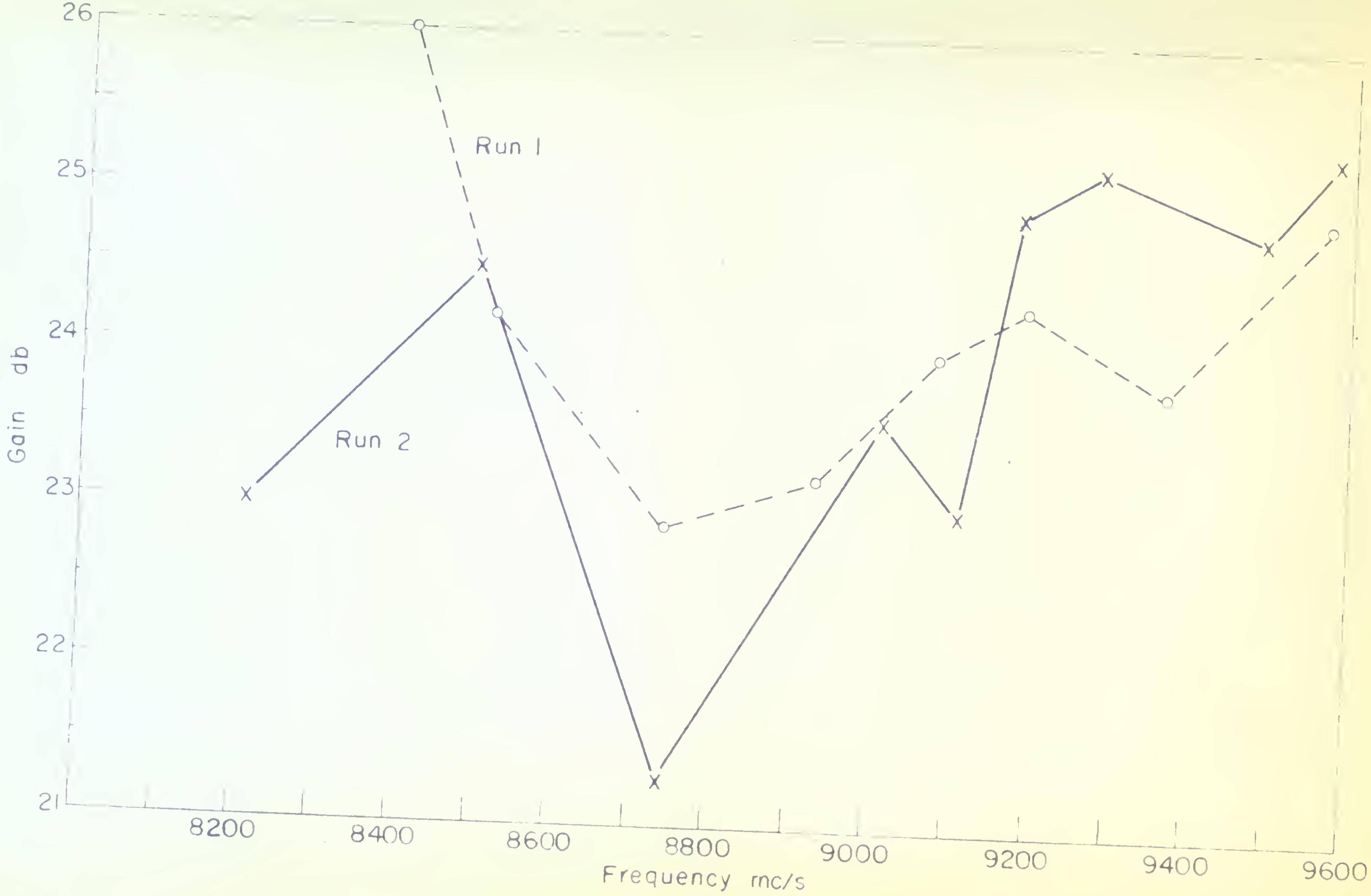


Figure 17 GAIN as a FUNCTION of FREQUENCY

Input Power 25 μw

Beam voltage adjusted for optimum gain Data obtained by measuring input and output power on separate W bridges

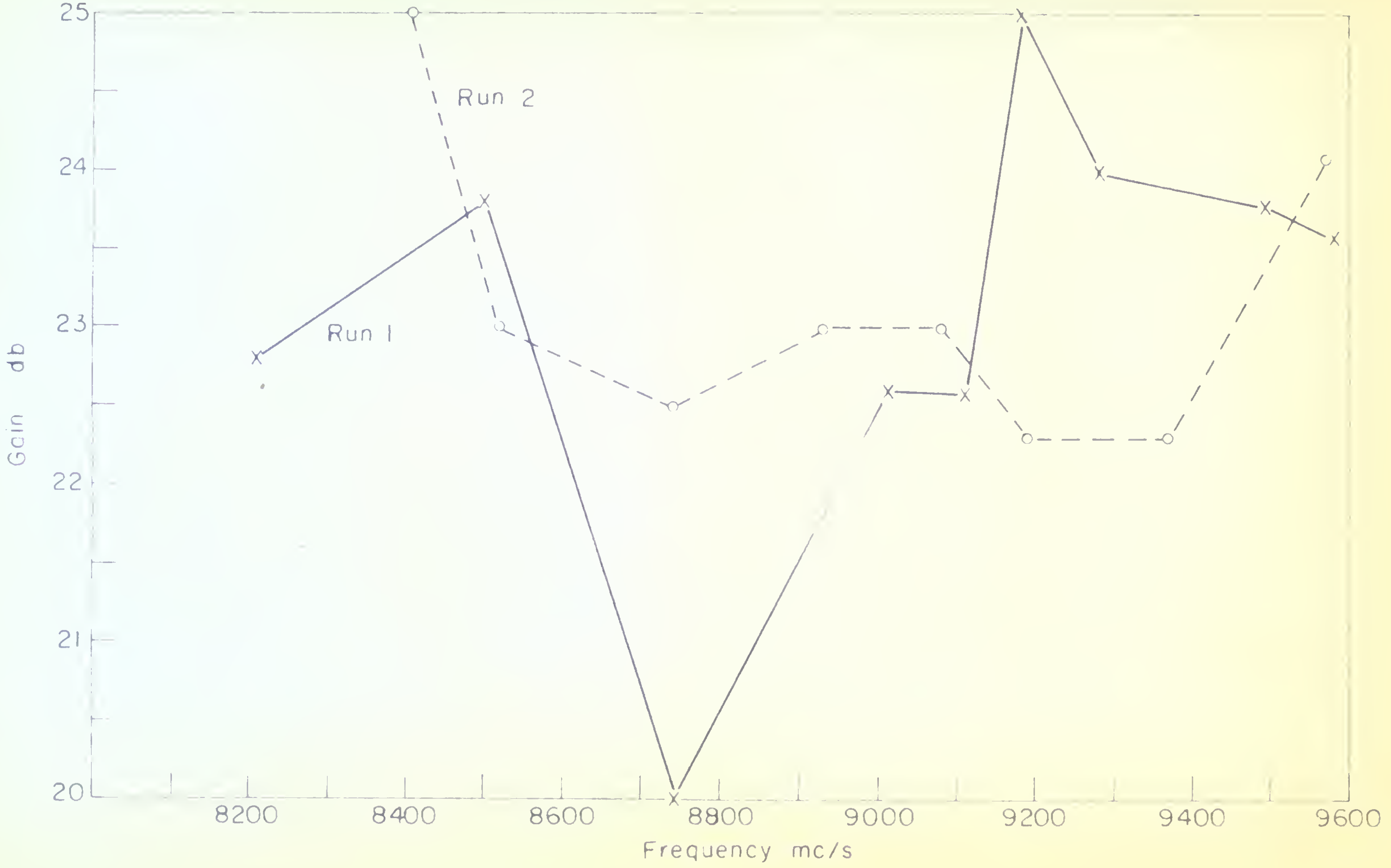


Figure 18 GAIN as a FUNCTION of FREQUENCY

Input Power 100 μw

Beam voltage adjusted for optimum gain. Data obtained by measuring input and output power on separate W bridges.

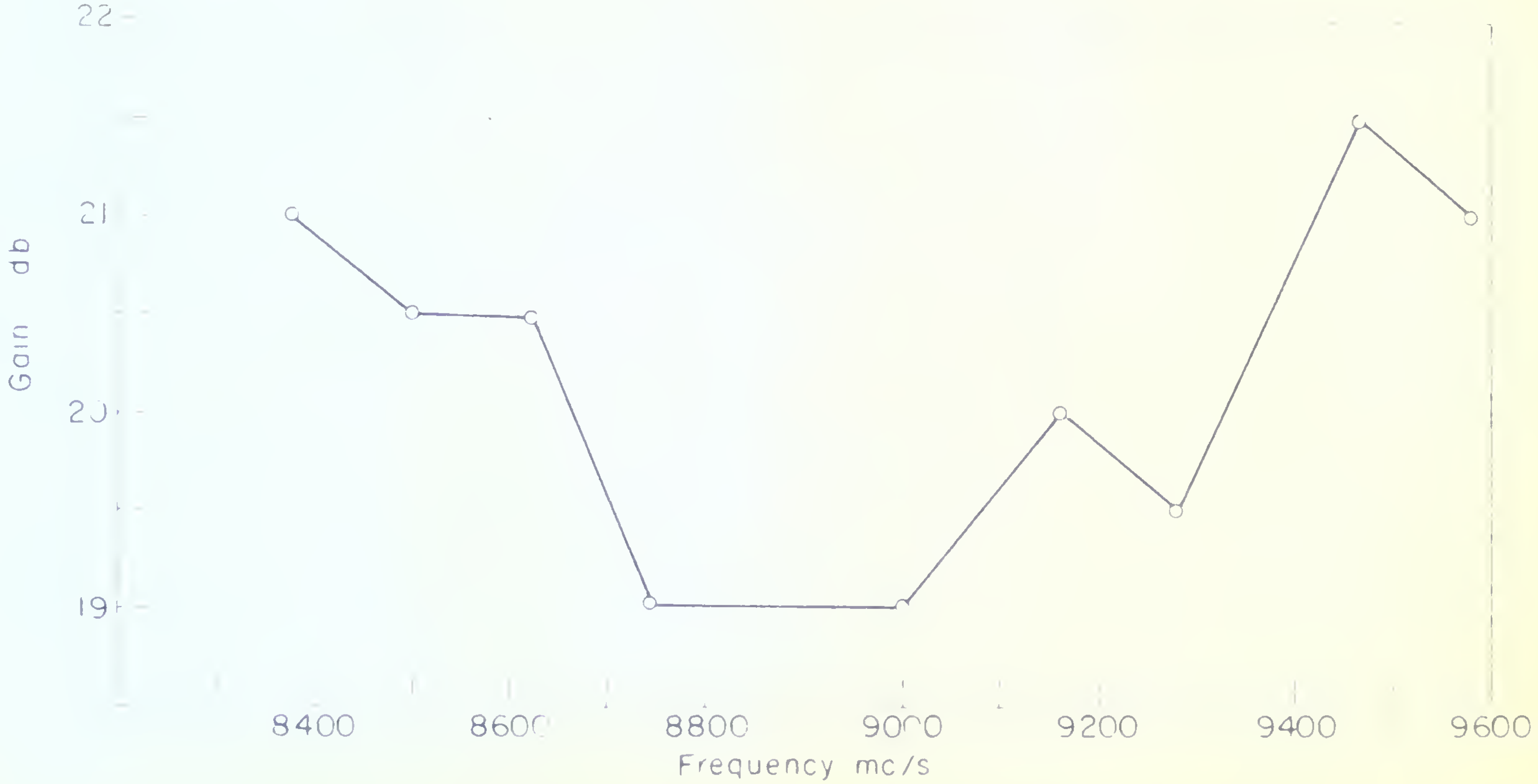


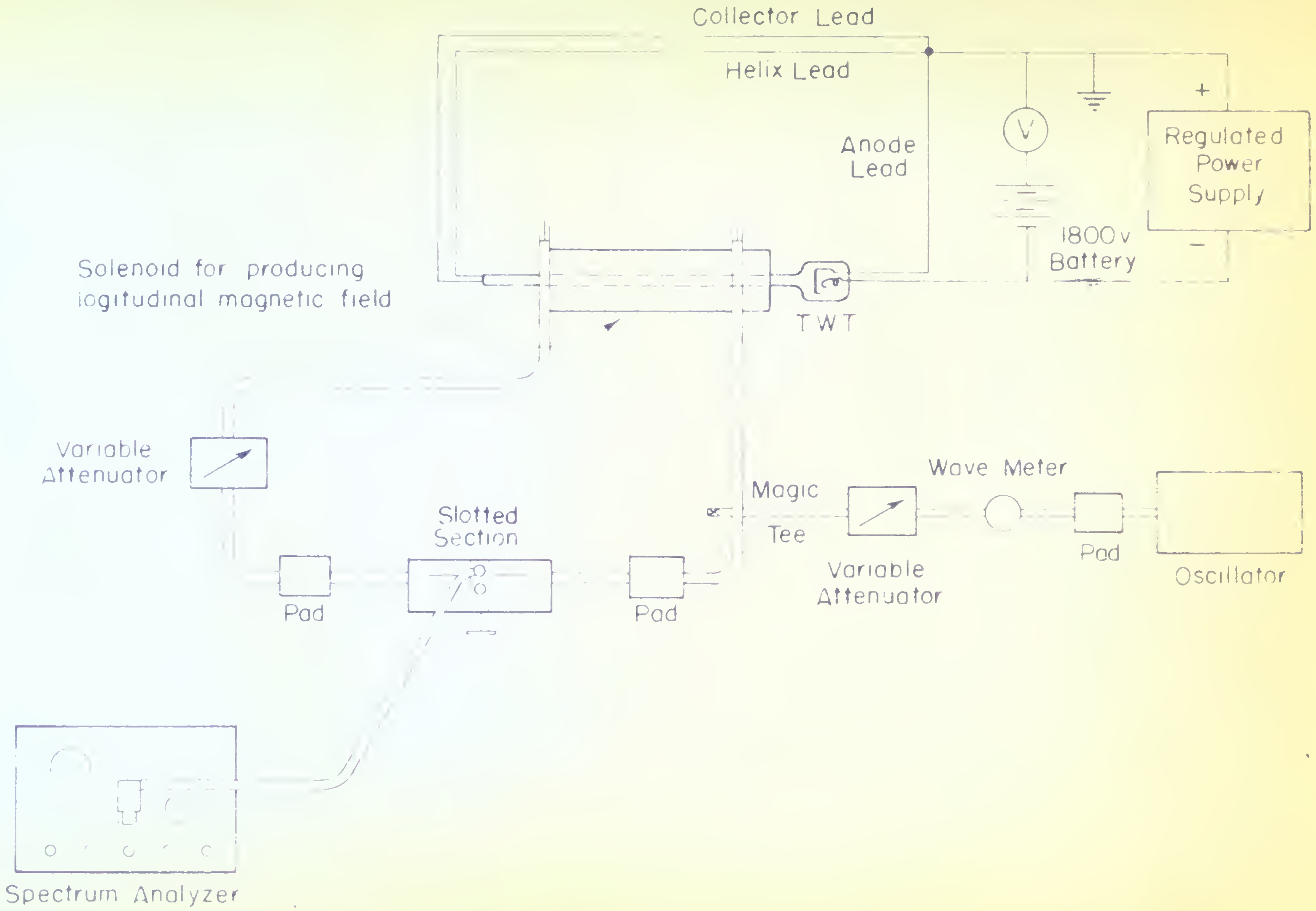
Figure 19 GAIN as a FUNCTION of FREQUENCY
Input Power 50 μw

Beam voltage adjusted for optimum gain Data obtained by shifting input of spectrum analyzer

tained by the two methods. The general shape of the curves is probably due to the frequency characteristics of the waveguide junctions at the tube. The frequencies used extend over the entire band available from a 2K25, reflex klystron, which is clearly not wide enough to establish the bandwidth of the amplifier. It would be safe to say, however, that the bandwidth of the amplifier is greater than 1200 megacycles per second.

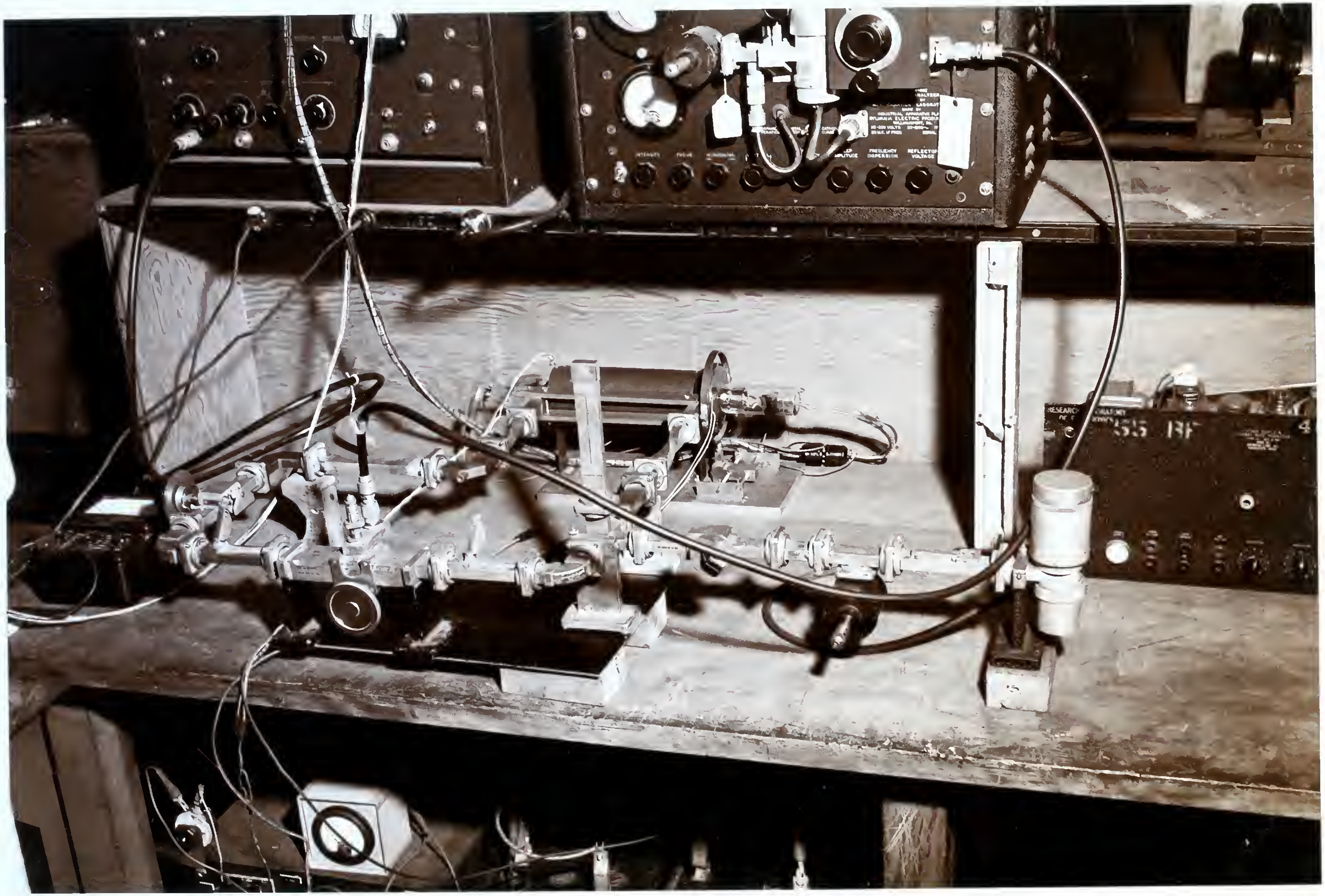
Phase Shift.

Measurements of the change of phase shift of the output referred to the input as a function of the beam voltage were made using the set-up which is shown schematically in Figure 20, and photographically in Figure 21. The method consists of introducing power directly from the oscillator and power from the amplifier output into opposite ends of the same slotted section. The variable attenuators are then adjusted so that the VSWR in the slotted section is very high. This makes the minima so sharp that their position can easily be determined to an accuracy of ± .2 mm. Then, while holding everything but the beam voltage constant, the shift of these minima is noted. The small changes in beam voltage are read by measuring the difference between the beam voltage and the voltage across a special high voltage battery. It is estimated that the incremental voltage can be measured to an accuracy of ± 1 volt using this arrangement, although the



SCHEMATIC of SET-UP for MEASURING PHASE SHIFT of OUTPUT for SMALL CHANGES in ACCELERATING VOLTAGE

Figure [illegible]



Set-up for Measuring Phase Shift

Figure 21

absolute voltage level may be 10 or more volts in error. With the mechanical position of all parts, including attenuator settings, held fixed, the electrical length of all the elements except the amplifier, is constant for any one frequency. Any shift in the location of the minima must therefore be due to a change in the electrical length of the amplifier. Since the mechanical length of the amplifier is also a constant this change in phase shift can be interpreted as a change in the phase constant of the amplified wave. A sample calculation of change in phase shift for a given shift of minimum is given below. A curve of incremental phase shift versus incremental beam voltage is shown in Figure 23.

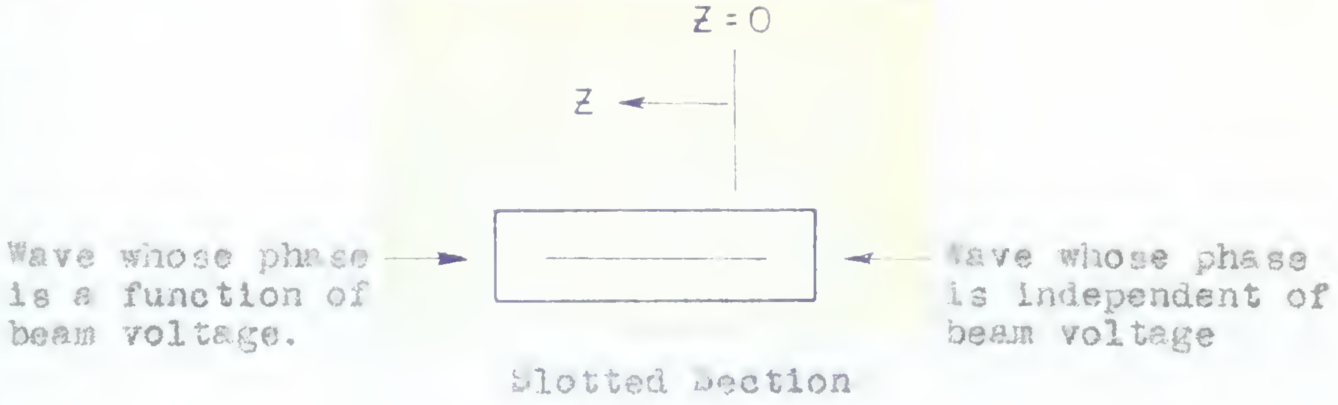

Z = 0
Z
Wave whose phase is a function of beam voltage.
Wave whose phase is independent of beam voltage
Slotted Section

Figure 22

Let wave traveling to left be $Ae^{-j\beta_g z}$.

" " " " right " $Be^{+j\beta_g z - j\phi}$,

where

β_g = phase constant in the slotted section, and

ϕ = phase angle by which wave B lags wave A.

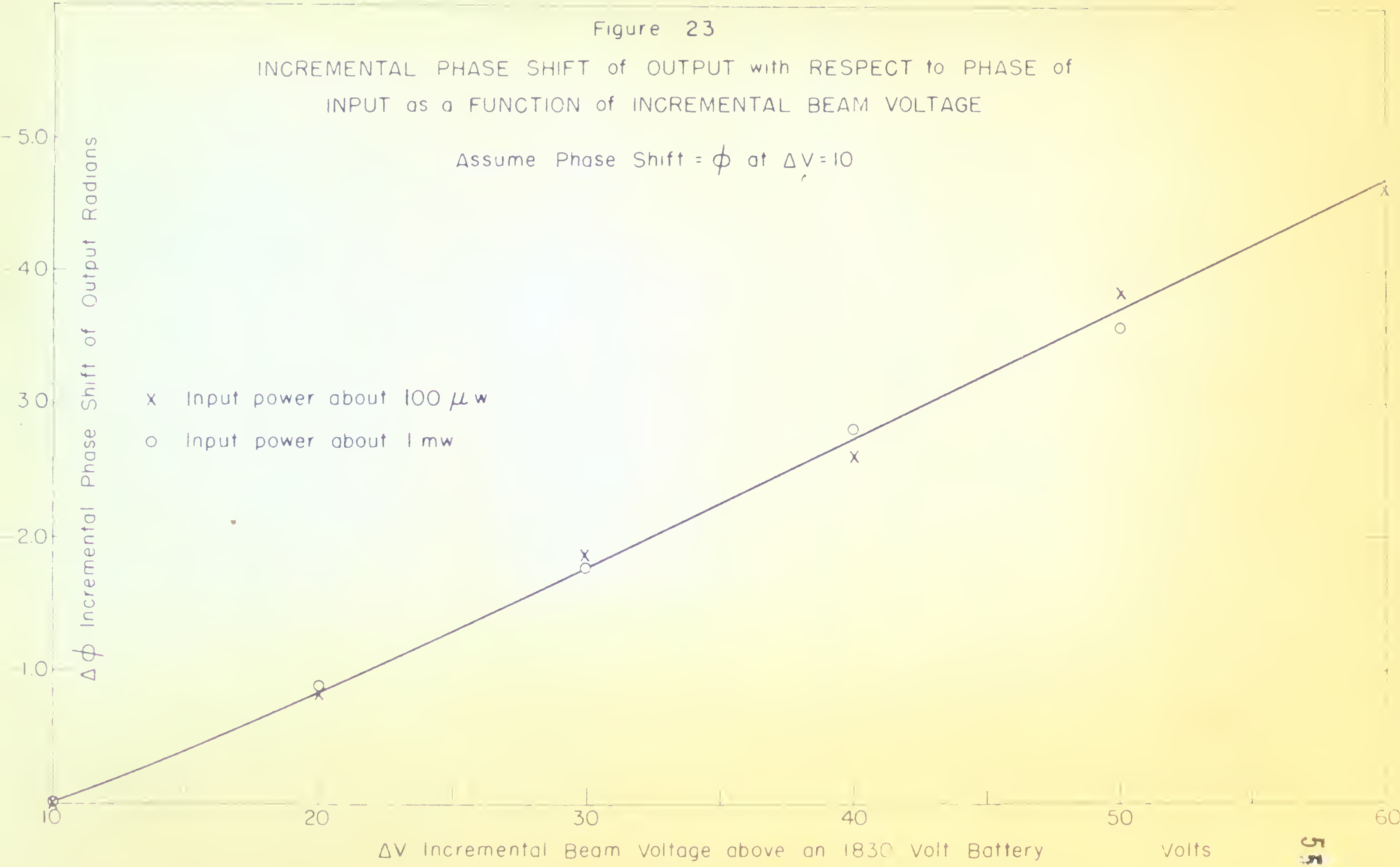


Figure 23

INCREMENTAL PHASE SHIFT of OUTPUT with RESPECT to PHASE of INPUT as a FUNCTION of INCREMENTAL BEAM VOLTAGE

Assume Phase Shift = ϕ at $\Delta V = 10$

Assume that the attenuators have been set so that $A = B$. Choose coordinates so that the sum of the waves is zero at $z = 0$ for all values of time.

Then $$A(e^{-j0} + e^{+j0 - j\phi}) = 0, \qquad (1)$$

and $$\phi = (2n+1)\pi. \qquad (2)$$

For a change in the phase shift $\Delta\phi$, the minimum will shift by an amount z so the sum of the waves may be written as

$$A(e^{-j\beta_g z} + e^{+j\beta_g z - j(\phi + \Delta\phi)}) = 0. \qquad (3)$$

Therefore $$-\beta_g z - \beta_g z + \phi + \Delta\phi = (2m+1)\pi. \qquad (4)$$

Subtracting (2) from (4) gives

$$-2\beta_g z + \Delta\phi = 2(m-n)\pi \qquad (5)$$

or $$\Delta\phi = 2\beta_g z + 2(m-n)\pi.$$

For $\Delta\phi < 2\pi$, $m = n$, and $\Delta\phi = 2\beta_g z$.

We now apply this result to solve for $\Delta\phi$ corresponding to a typical observed value of z. For the dominant wave in a rectangular waveguide filled with air

$$\beta_g = \frac{2\pi}{\lambda}\sqrt{1 - \left(\frac{\lambda}{2b}\right)^2}$$ where

λ = wavelength in free space, and

b = wide dimension of the waveguide.

The known conditions of operation for a typical case are

$z = 0.29$ cm,

$b = 0.9$ inches, and

$\lambda = 3.130$ cm.

Therefore $\Delta \phi = \frac{4\pi(0.29)}{3.130}\sqrt{1 - \left(\frac{3.130}{2(0.9)(2.54)}\right)^2} = 0.846$ radians.

There is no adequate theory for the case of a lossy helix so we cannot make a quantitative check between the observed and computed values of $\frac{\Delta \phi}{\Delta V_o}$. We can make a qualitative check by proceeding as follows. From the observations it is known that $\frac{z}{\Delta V_o} < 0$. Therefore, since we have chosen $\beta_g > 0$, $\frac{\Delta \phi}{\Delta V_o} < 0$. But $\Delta \phi$ may be written as $\Delta \phi = \Delta \beta_t z_t$ where

$\Delta \beta_t$ = incremental phase constant of the growing wave in the tube, and

z_t = length of the tube.

Since $z_t > 0$, $\frac{\Delta \beta t}{\Delta V_o} < 0$ which agrees qualitatively with the theory for a lossless helix[13].

Attempts to measure change in phase shift as a function of input power level were rather unsuccessful. Sharp minima could not be obtained at all power levels for the same settings on the variable attenuators. Any changes in these attenuators also introduce phase shift of an unknown amount. In addition to this, when a reflex klystron is operated near its maximum power output, any small change in the power output causes a change in the frequency. Due to the rather long electrical length of the amplifier and the waveguide, any change in frequency will upset measurements of change in phase shift by this method completely. The meager data that were obtained indicated that the change in phase shift as a

function of beam voltage is rather independent of power level, and that for a constant beam voltage, the change in phase shift as a function of power level is quite small.

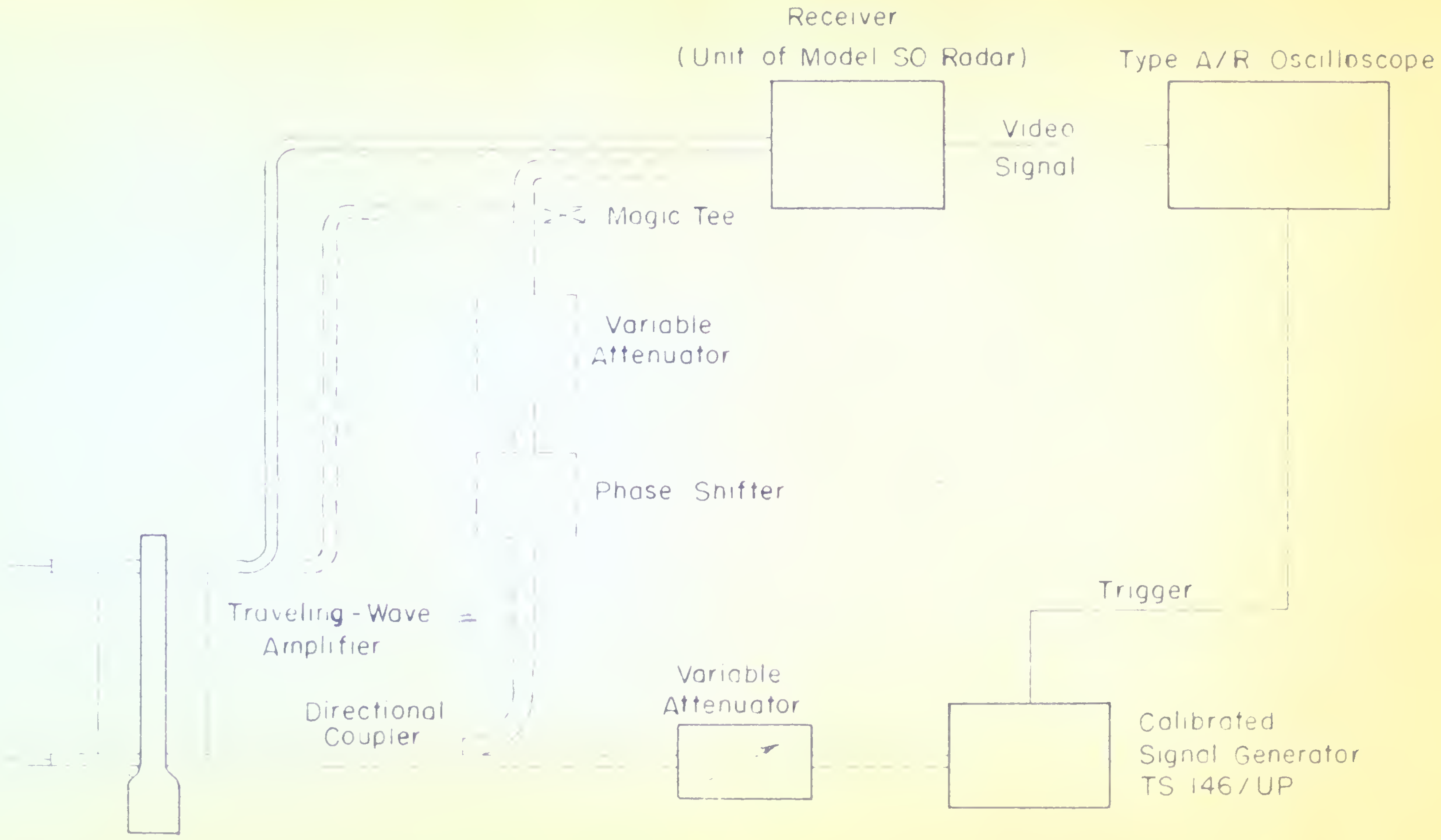
Noise Figure.

Noise figure measurements were made using the set-up shown schematically in Figure 24, and photographically in Figure 25. The output from the tube is fed into a conventional superheterodyne radar receiver employing a crystal mixer. The output of the receiver is fed into a type A/4 oscilloscope. A type 146 U/P signal generator is used to furnish a series of frequency modulated pulses. The generator includes a thermistor bridge and calibrated attenuators so that the peak power in the pulse can be set accurately. The procedure is to turn up the receiver gain until about one-half inch of noise appears on the oscilloscope. Then the signal generator is set so that the pulse is just discernible in the noise. This corresponds to an output signal-to-noise ratio of one. The signal power necessary to produce this condition is noted and the noise figure for the entire system is simply the ratio $\frac{\text{signal power}}{KTB}$, where

$K = 1.38\text{x}10^{-23}$ Joules per degree absolute,

T = Absolute temperature of system taken as 300°, and

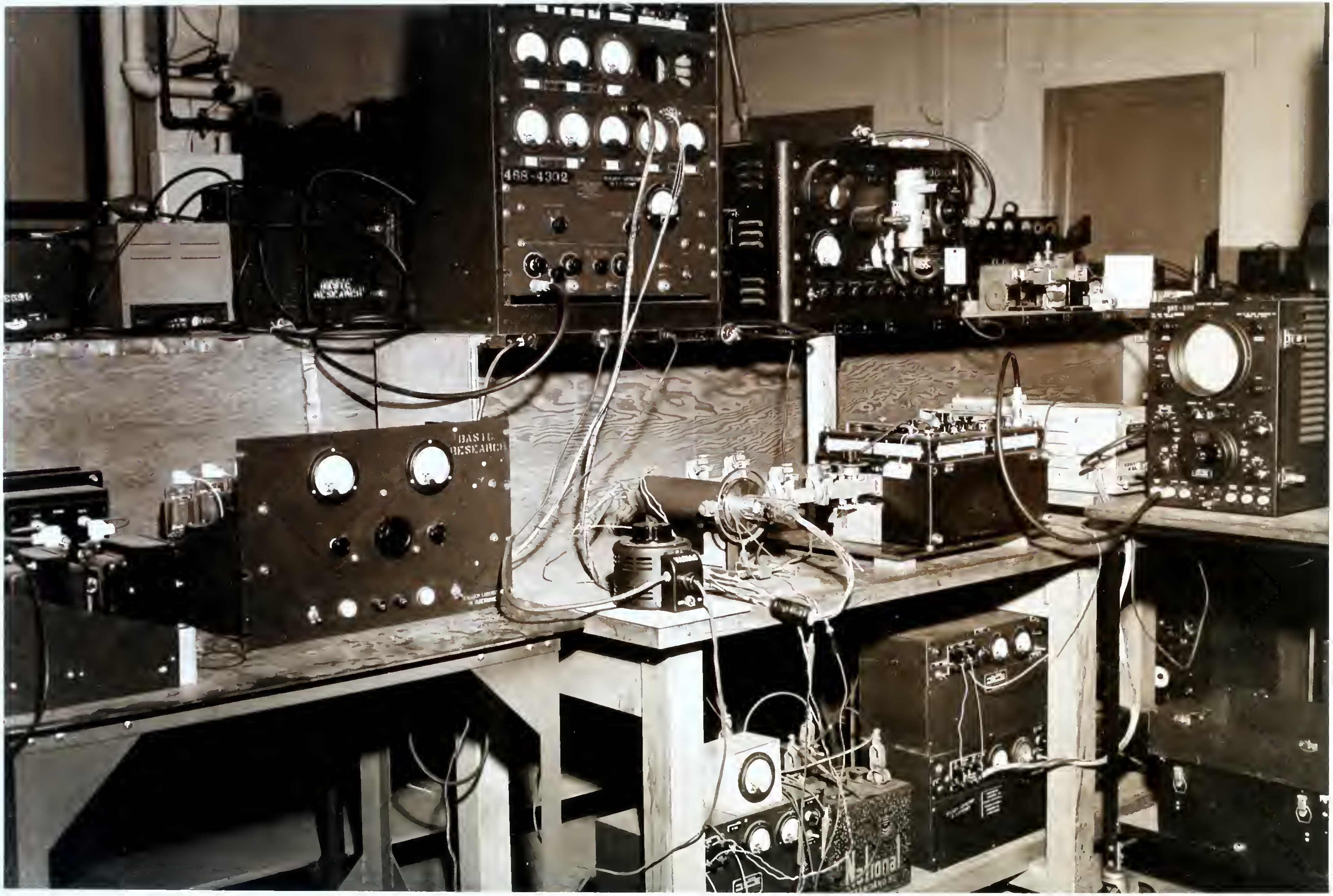
B = Effective bandwidth of the system which in this case is taken as $2\text{x}10^{6}$, the effective bandwidth of the receiver.



SET - UP for MEASURING NOISE FIGURE

Connection between amplifier and receiver is shown solid for basic set-up and dashed for set-up as modified to provide feed back

Figure 24



Set-up for Measuring Noise Figure

Figure 25

Since the dial of the signal generator reads in db below a milliwatt it is convenient to convert KTB to 110.8 db below a milliwatt. The noise figure in db for the system is then found by merely subtracting the dial reading from 110.8. The formula for finding the noise figure F_1 of the first of a series of elements in cascade, when the overall noise figure is known, is[14] $F_1 = F - (\frac{F_2-1}{G_1})$

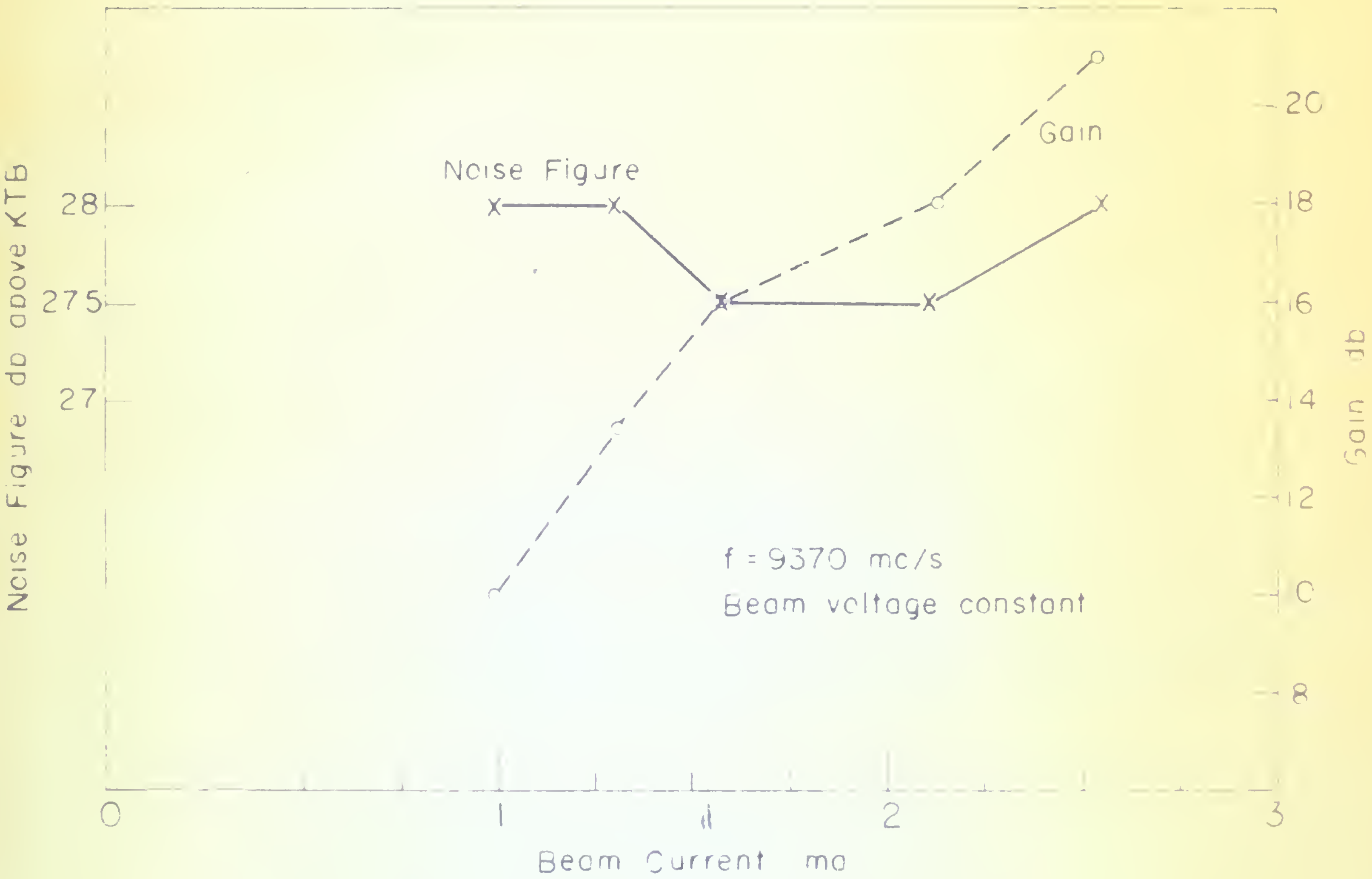
where F = Noise figure of entire system,

F_2 = Noise figure of entire system with the first element omitted, and

G_1 = Power gain of the first element.

Since the tube being considered has a power gain of over 10, clearly the noise figure of the tube is simply the noise figure of the entire system of which the tube is the first element.

Figure 26 shows the noise figure for various values of total beam current. For these measurements the total beam current was varied by putting a negative voltage on the cathode electrode. The components of the total noise generated in the tube are shot noise and partition noise. Shot noise depends on the magnitude of the beam current, while partition noise depends on the percentage of the beam current getting through to the collector. It appears that the principal noise source in this tube is the partition noise since the percentage of beam current getting through to the collector is nearly independent of the magnitude of the beam current.



NOISE FIGURE and GAIN as a FUNCTION of TOTAL CURRENT LEAVING GUN

For all points total current divided approximately
35% to helix
65% to collector

Figure 26

Tests, which were by no means exhaustive, were made of a scheme for improving the noise figure by the use of positive feedback. The basic set-up for measuring noise figure was modified as shown by the dashed lines of Figure 24. The procedure here is to adjust the phase shifter in the feedback line so as to maximize the signal. This should give increased signal power out, whereas the noise, which is completely random, should be unaffected by any phase shift introduced in the feedback line. It is expected that the net result would be an improvement in the noise figure. The results obtained were negative. It was possible to maximize the signal using positive feedback, but under these conditions the noise figure was the same as for no feedback. By adjusting the phase shifter for negative feedback it was possible to make the noise figure somewhat worse than for no feedback. Under some conditions the phase shifter did exhibit an effect on the noise which is contrary to expectations. No explanation of this effect can be given at this time.

CHAPTER IV

CONCLUSION

Verification of the Theory.

The basic problem undertaken was to realize an increase in stable gain over that exhibited by the earlier tubes of the program. That this was accomplished in two similar tubes provides additional verification of the theory, and indicates increased understanding of the factors which primarily control gain and stability. The measurements of the effect of beam voltage on the phase velocity of the growing wave serve as a qualitative check on one particular aspect of the theory. Although this effect had been noted earlier, there is no prior record of careful measurements of this effect extant in the literature. The theory, as now understood, applies primarily to small-signal operation. The effect of higher level operation on optimum beam voltage and the saturation effect, which were noted, are predicted by the present inadequate large-signal theory. Even the present small-signal theory is inadequate in that it does not predict the nature, amount, and location of the intentional loss, introduced to suppress oscillation, for optimum performance. The decision to use concentrated loss, both inside and outside the dielectric shell, and located somewhat nearer the input end of the helix, was based on qualitative thinking and on unpublished information obtained from the General Electric Company. There is

no reason to believe that the optimum loss configuration was used. It is clear that this loss arrangement is superior to that used in the earlier tubes since the oscillations were completely suppressed.

Limitations.

The principal limitations of these tubes for low-level operation are the high noise figure and the bulk of the auxiliary items such as focusing coils and power supplies. The latter is not serious but is merely a matter of engineering design. Just how serious the former is will not be known until the design is perfected to the point that shot noise and partition noise are at an irreducible minimum.

Suggestions for Future Study.

A concerted effort should be made to perfect the electron gun design. The gun should not be considered alone, but the gun and the beam focusing outside the gun should be treated as a composite problem. An improved gun and focusing combination should aid materially in reducing the partition noise.

Improvements are possible in the design of the r-f coupling between the helix and the external circuits. Specifically, these couplings should be made more broadband. They should be designed so that the tube can be removed or inserted at will, but in such a manner that upon insertion of the tube, the coupling will be positively and

securely established. The design should be such that radiation into space is nearly equal to zero.

Further measurements of the effect of positive feedback should be made to establish the maximum stable gain that can be attained, and the effect on bandwidth. The incomplete data that were obtained in connection with the effect of feedback on noise indicated that under certain conditions there was a change in the noise as a result of changes in the phase shift of the feedback line. This would not be expected of noise that is completely random. Careful investigation of this phenomenon may reveal some useful information as to the noise sources in the tube.

A study should be made of the possibilities of modulating a traveling-wave amplifier. The usefulness of phase modulation, which is possible by varying the beam voltage, should be investigated. As a variation of this the amplifier might be converted to a stable oscillator by the use of controlled feedback, and an investigation made of the effect of beam voltage on the frequency of oscillation.

APPENDIX

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